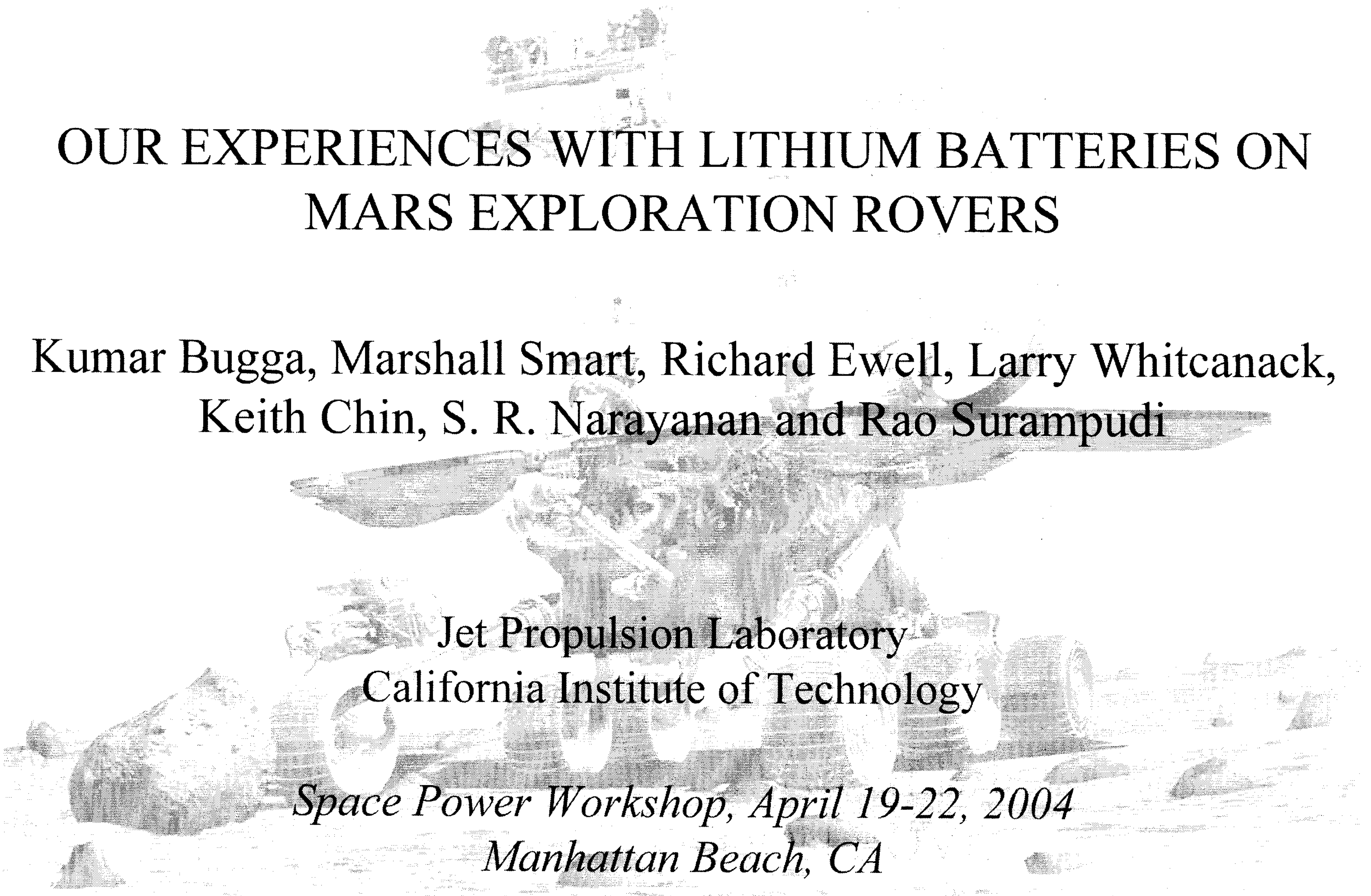

OUR EXPERIENCES WITH LITHIUM BATTERIES ON MARS EXPLORATION ROVERS

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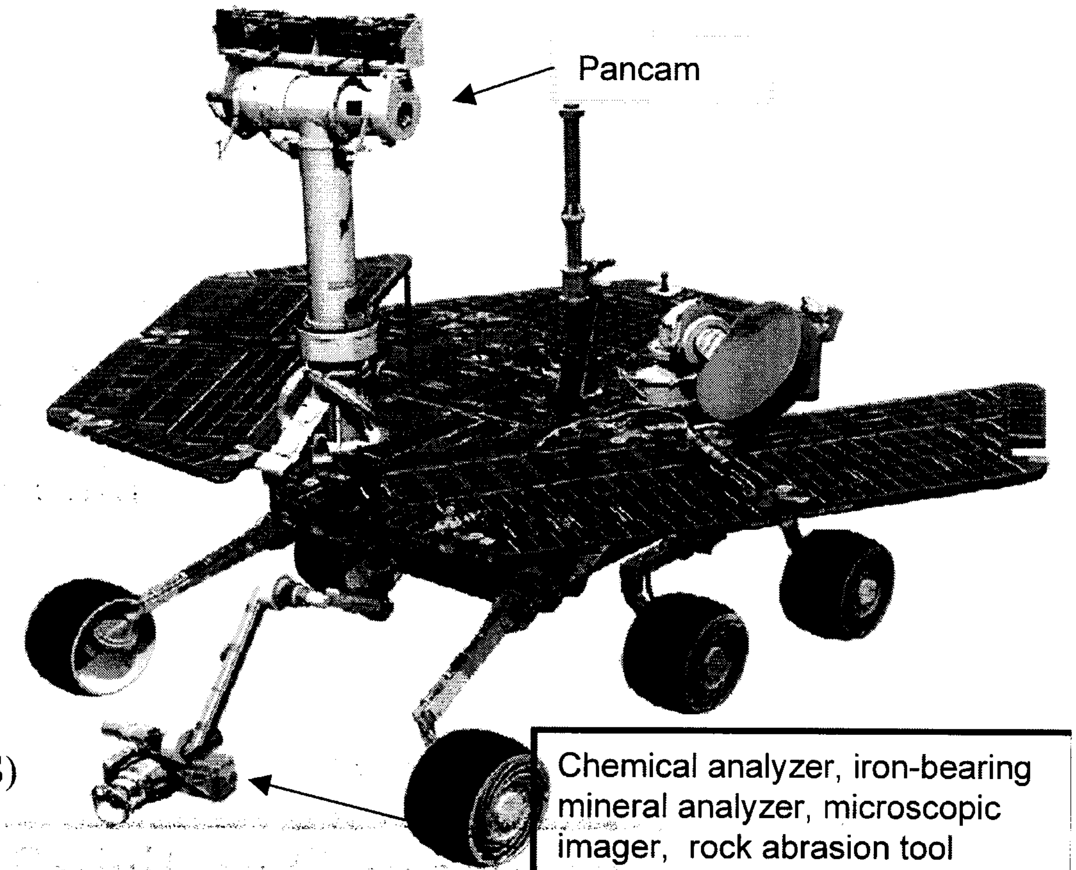
Outline

- Introduction on MER batteries.
- Rover Battery Impedance
- Depassivation of Lander batteries
- Flight data from Spirit and Opportunity
- Rover Battery Ground test data
- Conclusions

Deployed Rover (Spirit or Opportunity)



Spirit and Opportunity

- NASA's twin robot geologists, the Mars Exploration Rovers, Spirit and Opportunity launched toward Mars on June 10 and July 7, 2003, in search of answers about the history of water on Mars.
- Both landed successfully January 3 and 24, respectively, on either side of Mars.

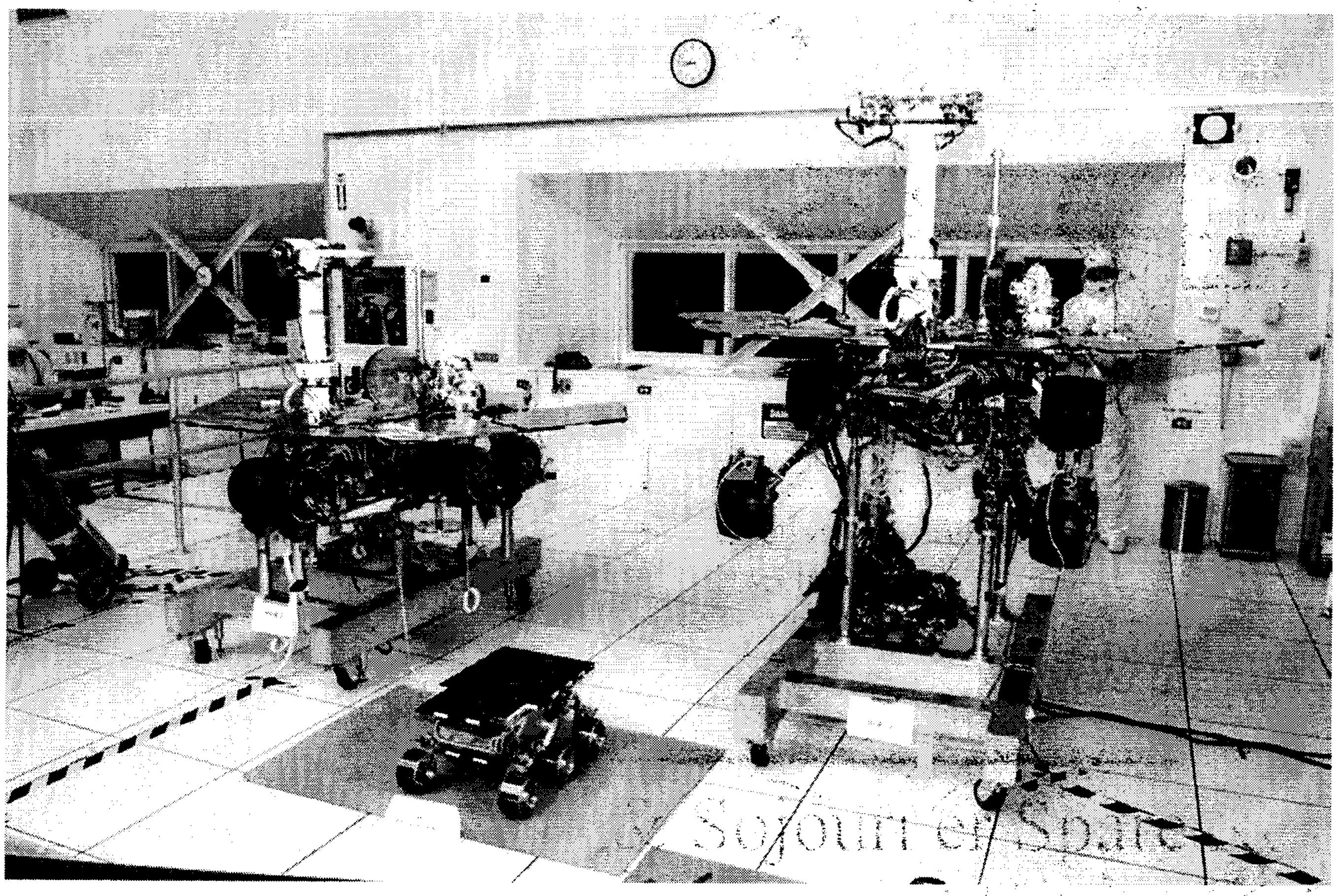
Payload

- Panoramic Camera (Pancam).
- Miniature Thermal Emission Spectrometer (Mini-TES)
- Mössbauer Spectrometer (MB)
- Alpha Particle X-Ray Spectrometer (APXS)
- Magnets
- Microscopic Imager (MI)
- Rock Abrasion Tool (RAT)

To Date

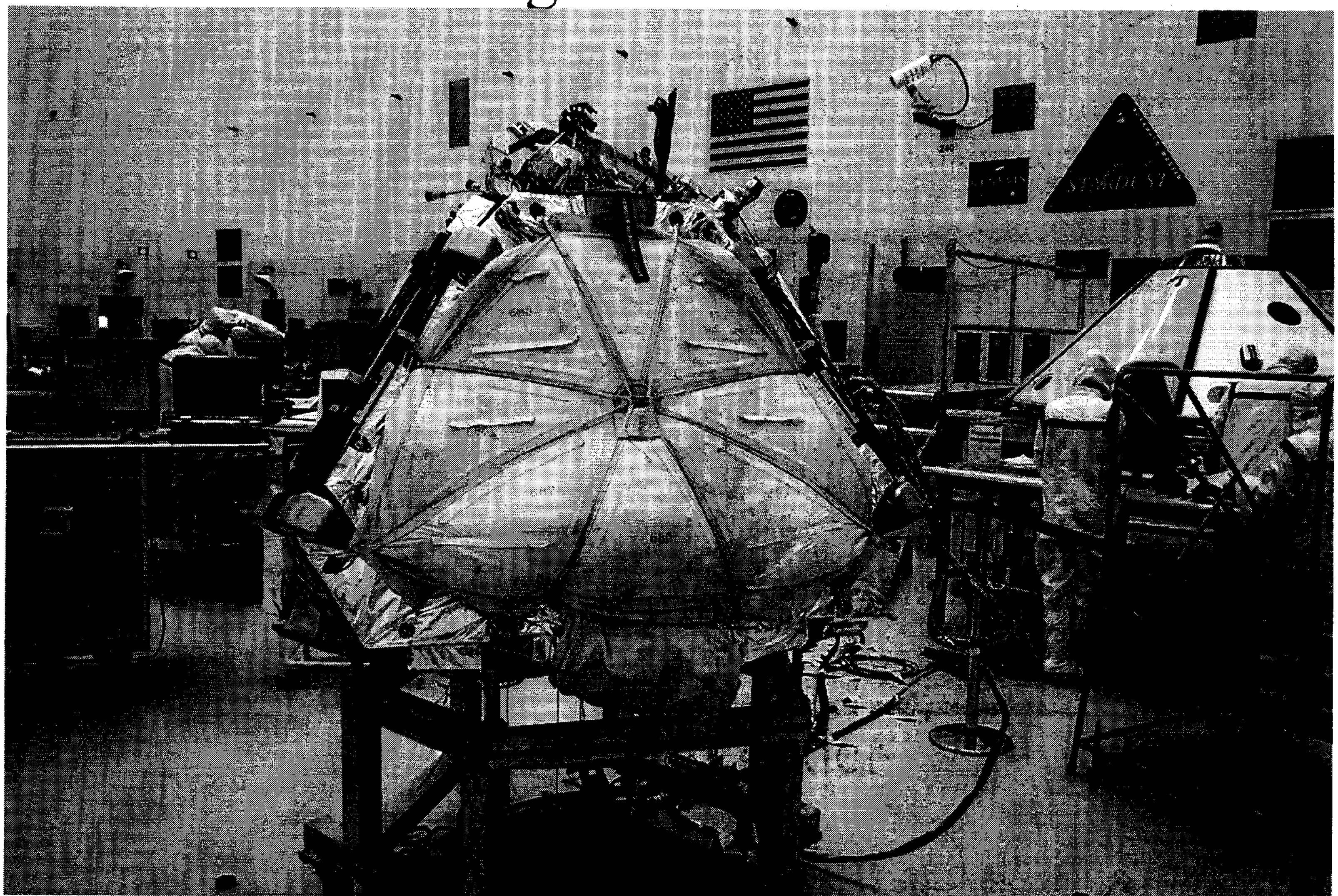
- Several astounding observations made by both Rovers.
- Conclusive evidence for past water.
- Over 90 sols completed by Spirit and Opportunity is well on its way.
- Mission extended through Oct 04.

MER #1, MER #2, & Sojourner Spare Rovers

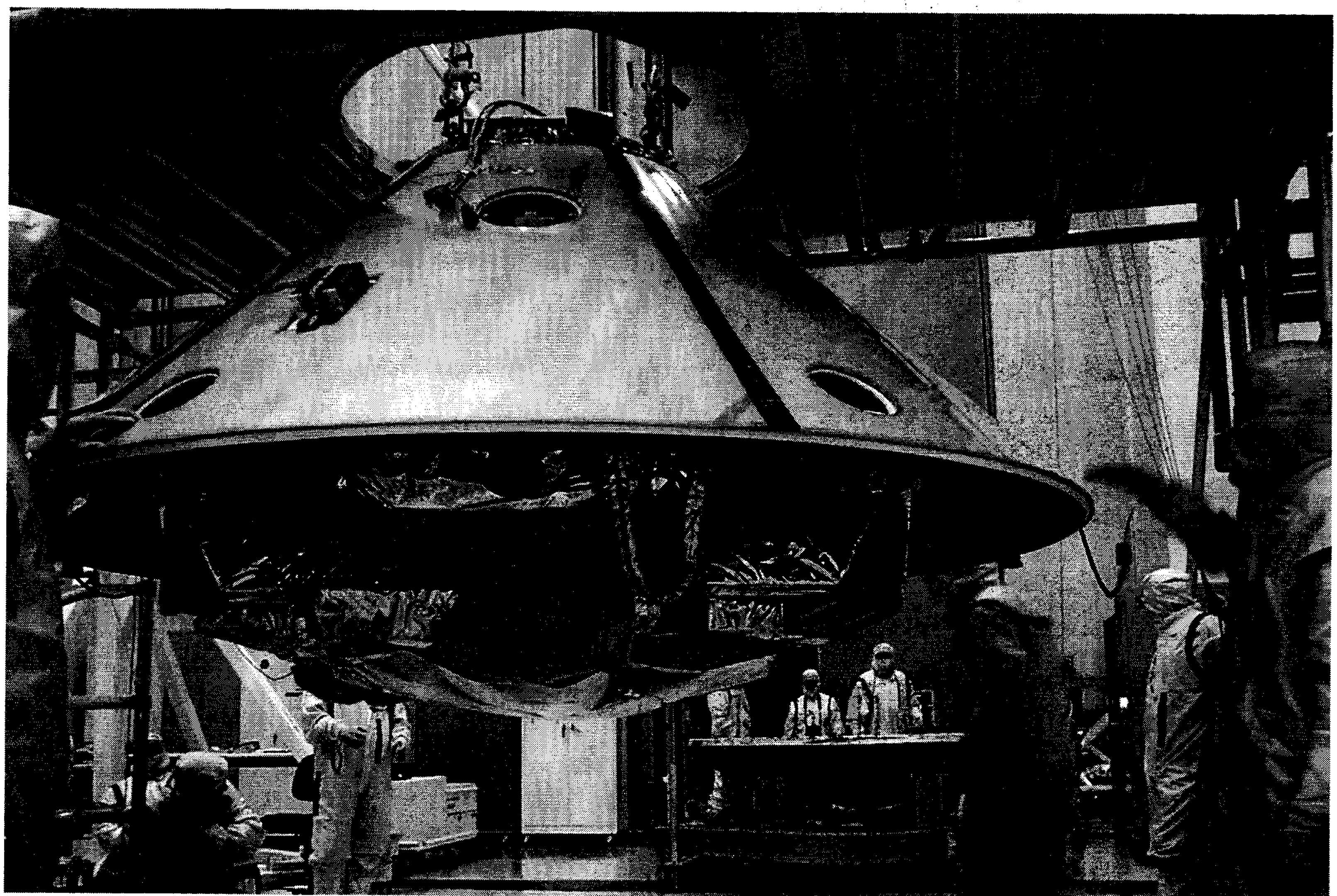


- ~Ten times as big as the Sojourner Rover on Mars Pathfinder mission (1995).
- Contains Rechargeable, lithium-ion batteries, unlike Sojourner (primary Li-$SOCl_2$)

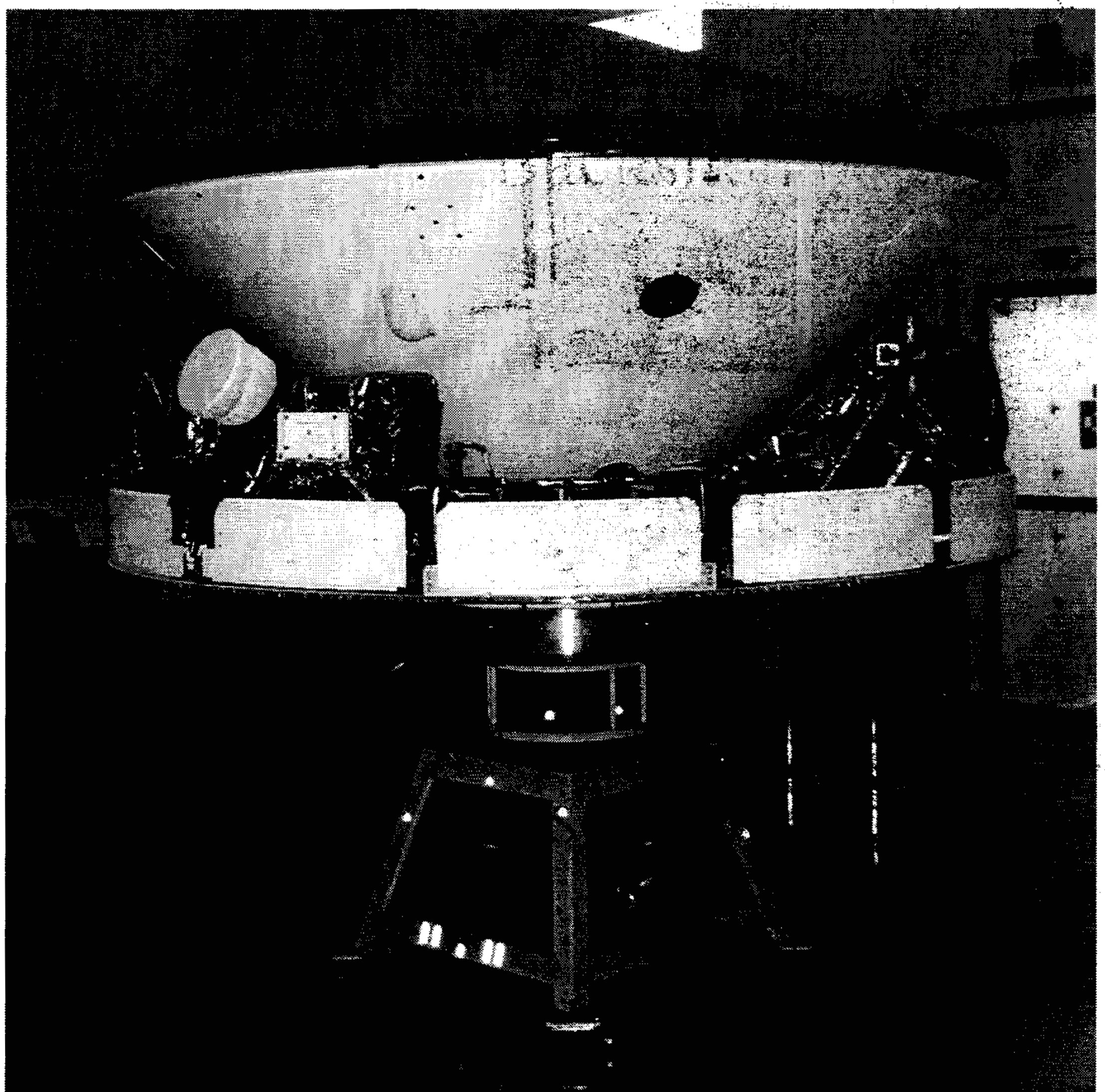
Integrated Lander



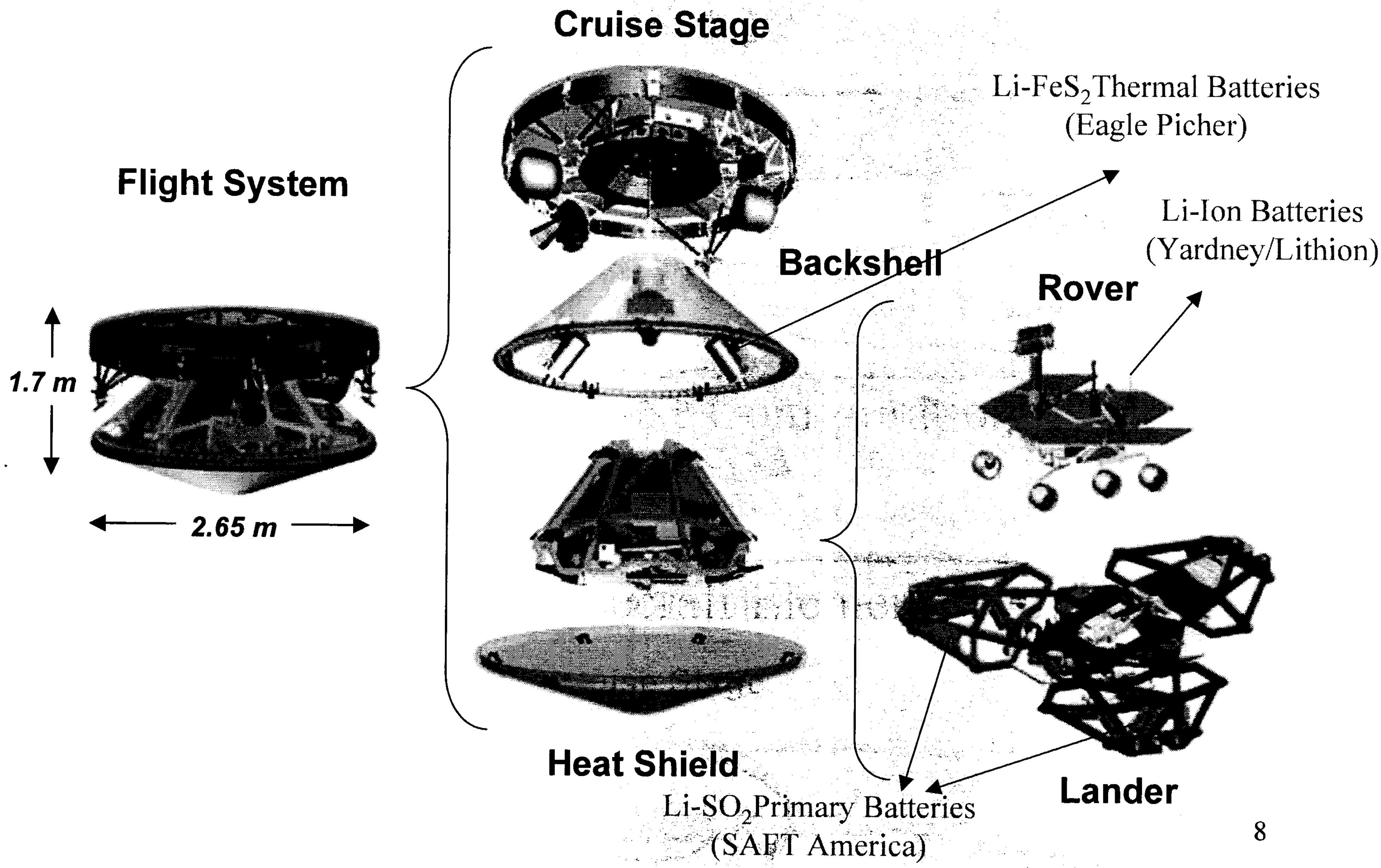
Lander in Backshell



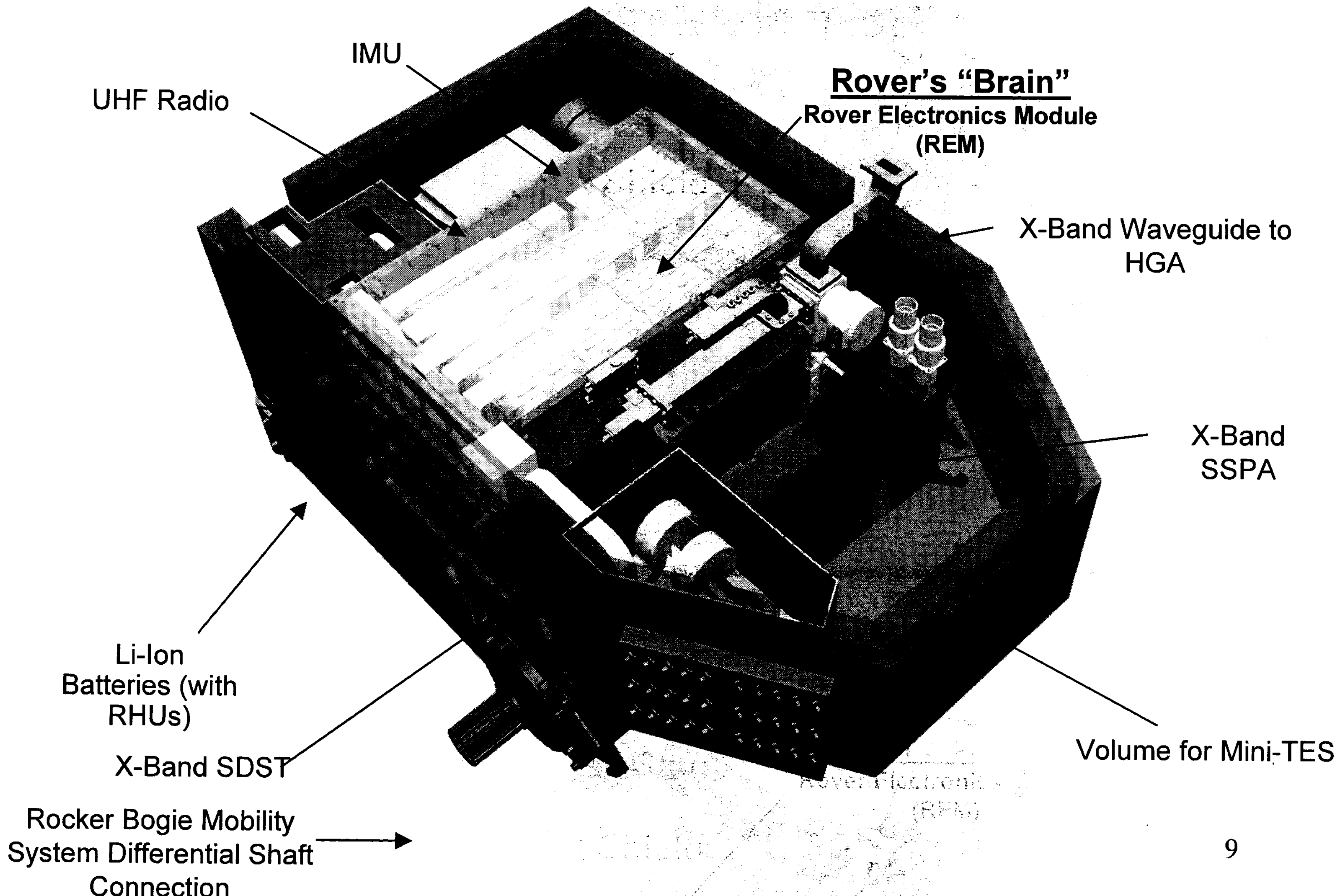
Launch / Cruise Configuration



Major Spacecraft Elements

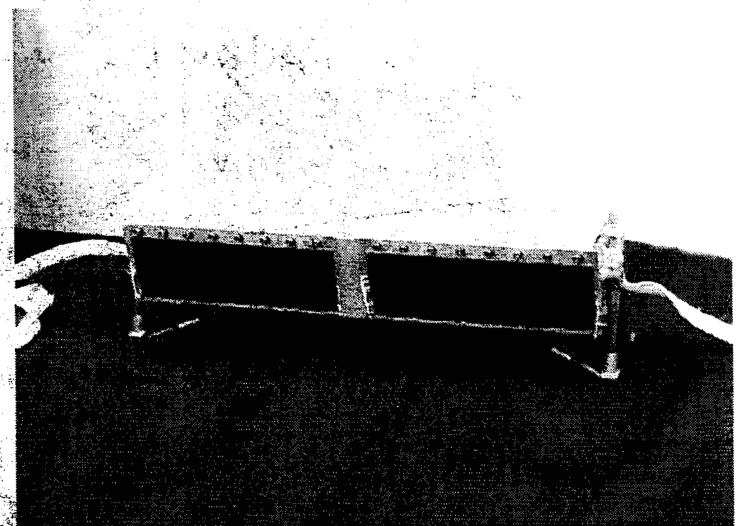


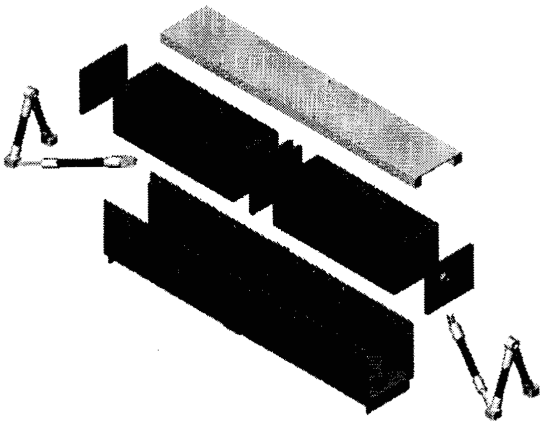
Inside the Rover (Warm Electronics Box)



Rover Battery Assembly Unit

Advanced Li-ion cell for MER (10 Ah).
With Improved low temperature capability.
Technology developed by JPL/NASA/DoD





Advanced Li-ion battery for MER.
Two such batteries connected in parallel are located inside the Warm electronics Box.

- Two parallel batteries each with eight (10 Ah) Li-ion in series - 30 V, 16 Ah (480 Wh).
- Fabricated by Yardney Technical Products, CT (Lithion)

Evolution of MER Rover Batteries

Li Ion Batteries From Laboratory to Mars

- **Low Temperature Electrolyte Development : JPL (92-96)**
  - Mars Exploration Program
- **Cell Development: AFRL, NASA GRC, JPL, RDECOM, (97-01)**
  - Yardney Technical Products
- **Performance Database Dev. : JPL, NASA-GRC (97-03)**
- **Flight Hardware Design & Fabrication: JPL, Yardney (01-03)**
- **Battery Operational Strategies: JPL (02-04)**

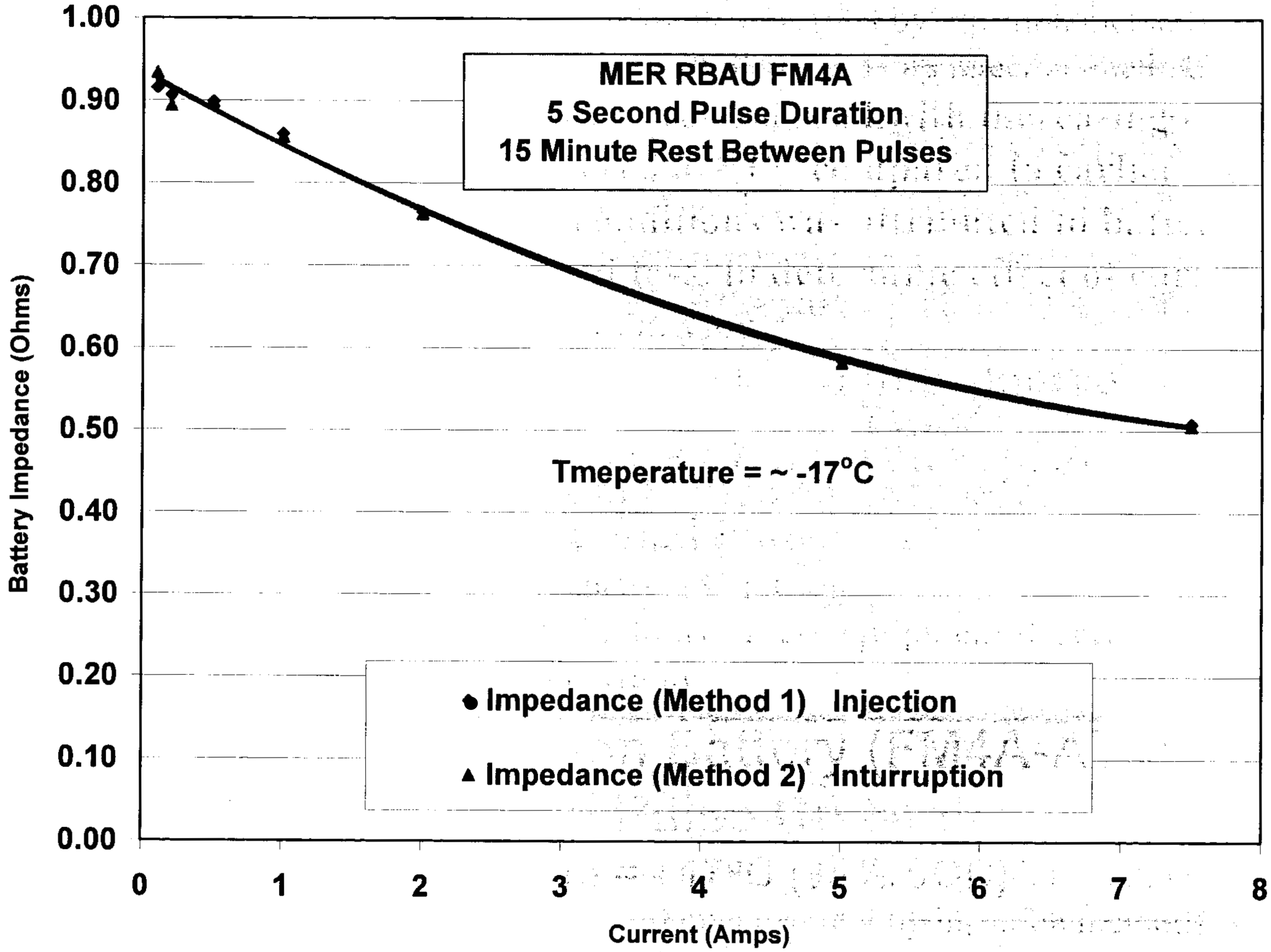
Rover Battery impedance too low?

- One of the pyros in series with the battery failed closed in the ATLO test, which led to a significantly high current to flow through the chasis and ground, thus blowing a 5 A fuse in between.
- Should the same thing happen on the spacecraft, the spacecraft will be floating, as opposed to the desired "grounded" condition.
- A current limiting (12 A?) resistor in series with the RBAU and the squib would be stressed, if higher currents are passed through this.
  - ✓ For once, a higher battery impedance (at $-16^{o}C$) is desirable (about 400 mOhms) from this point of view.
  - ✓ Battery impedance value is in the critical path of whether to proceed with the planned launch or not.

MER 8 Ah Rover Lithium-Ion Battery

- Initial Testing of FM4A- Current-Interrupt Impedance Measurements
  - **5 A, 60 second duration, three temperatures (20, 0, -20)**
    - Temperature = 20°C, Impedance = 123 mOhms
    - Temperature = 0°C, Impedance = 251 mOhms
    - Temperature = - 20°C, Impedance = 606 mOhms
  - **30 A, 50 mSec duration (42 total), two temperatures (0, -10)**
    - Temperature = 0°C, Impedance = 104 mOhms
    - Temperature = -10°C, Impedance = 133 mOhms
    - **Values questionable due to inability of test equipment to record data accurately in such short time frames**
  - **5 A, 60 second duration, temperature = -16°C (~ 17.4 °C)**
    - **Multiple current levels studied**
    - Current = 2.5 A, Impedance = 834 mOhms (857 by injection method)
    - Current = 5.0 A, Impedance = 670 mOhms (694 by injection method)
    - Current = 7.5 A, Impedance = 582 mOhms (603 by injection method)
    - **Lower impedance values were observed with increasing current**
    - **Higher impedance observed at –17° compared to earlier measurement at –20° under the same conditions was attributed to battery aging effects**
    - **Results led to initiation of tests to determine effect of current and pulse length upon impedance behavior.**
- With 1 kHz mOhm meter (HP) : Impedance at -16°C = ~ 200 mOhms

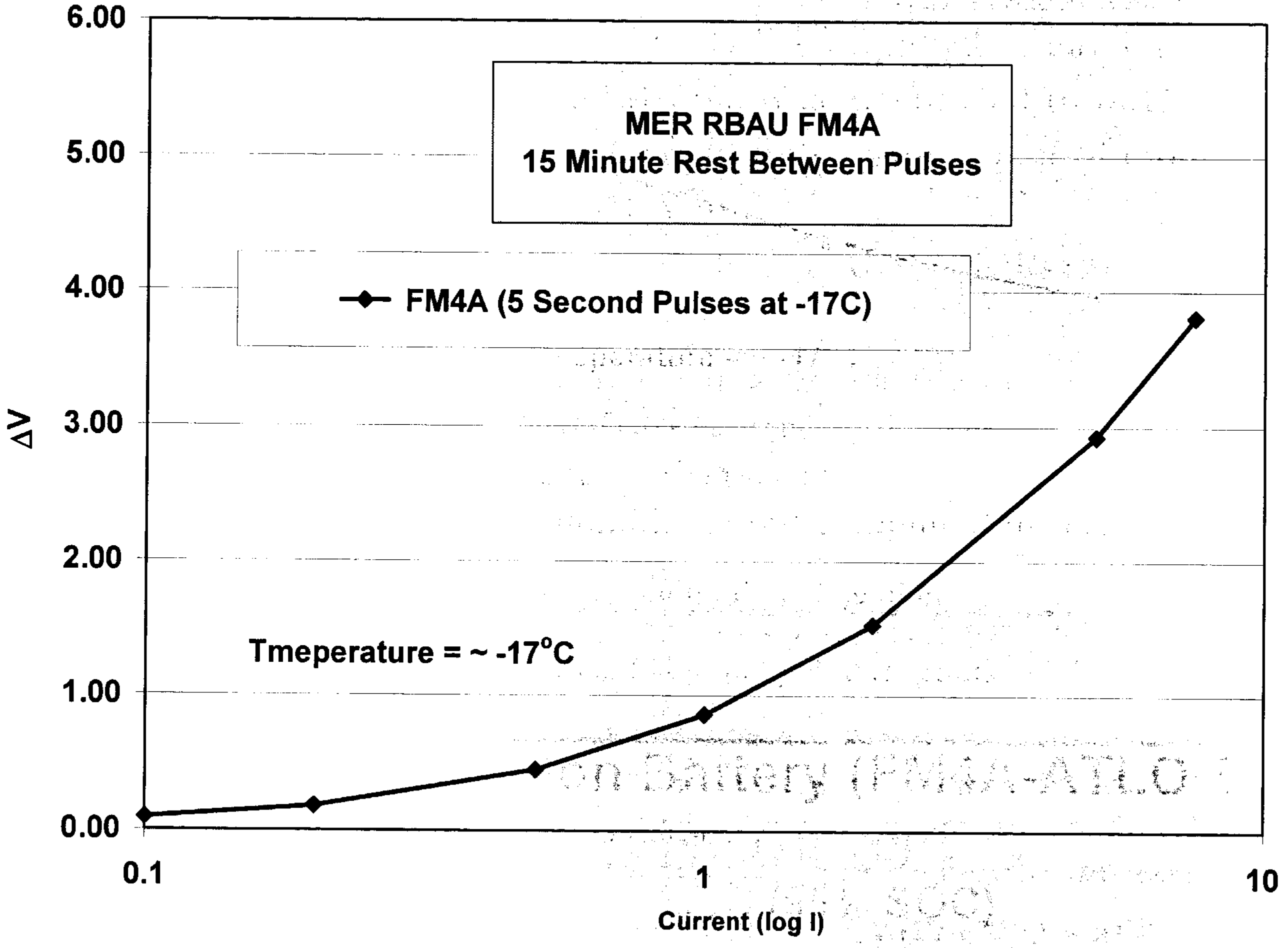
MER 8 Ah Rover Lithium-Ion Battery (FM4A-ATLO Battery)
Effect of Pulse Current
Temperature = - 17°C (95% SOC)



- Similar trend as with longer (60s) pulses. Thermal effects are insignificant.

MER 8 Ah Rover Lithium-Ion Battery (FM4A-ATLO Battery) Effect of Pulse Current

Temperature = - 17°C (95% SOC)



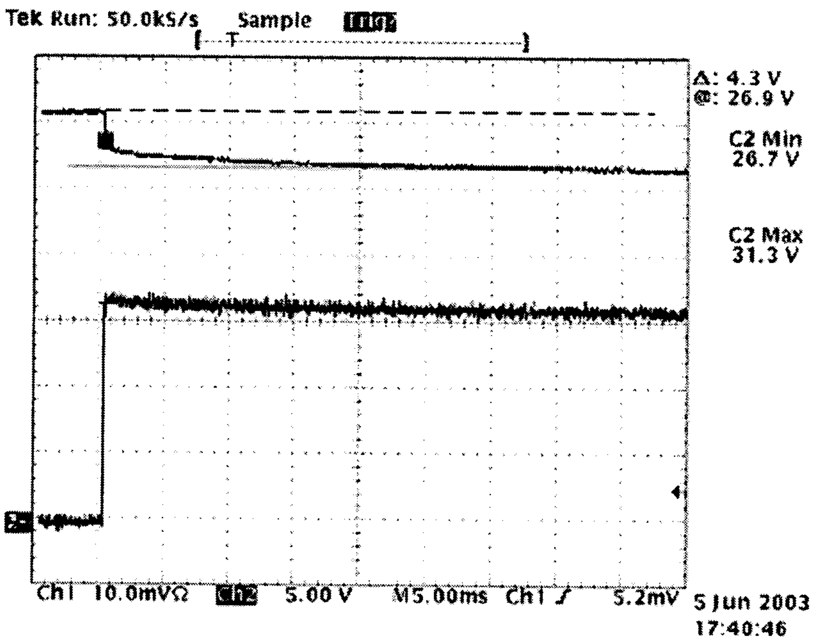
- A Tafel-like behavior (linearity between voltage and log I) expected.
- Non-linearity at high currents suggests contributions from mass transfer effects

MER 8 Ah Rover Lithium-Ion Battery (FM4A-ATLO Battery)
Current–Interrupt Impedance Measurements
Temperature = - 16°C (~ 90% SOC)
Effect of Pulse Duration on Impedance

Current (A)	Pulse Time	Δ V	Impedance (mOhms)
12	30	1.9672	164
12	50	2.154	180
12	75	2.4415	203
12	100	2.5812	215
12	125	2.7003	225
12	150	2.8614	238
12	1000	4.6601	388
12	5000	5.1642	430

- **With increasing pulse width, the mass transfer contribution increases, thus resulting in a higher impedance.**

MER 8 Ah Rover Lithium-Ion Cells/Battery Results of Scope Measurements



Results at –16°C.

Load	Impedance
5	260 mOhms
11	263 mOhms
17	287 mOhms

- **Rapid data capture for short pulses.**

- Lower impedance values (260 to 280 mOhms at 11-16 A) confirmed.
- We had some additional relief in the form of lower temperature –18°C, which made these estimates conservative- Green light for launch.
- Interestingly, the fuse did blow on both Spirit and Opportunity: Both spacecraft are in the 'floating' mode

Electrode voltage may be expressed as:

$$E = E_{OC} - \eta_{Ohmic} - \eta_{Ch.Tr} - \eta_{Diffusion}$$

1) **Ohmic : Constant with time but increases linearly with current.**

2) Charge Transfer or Kinetic :

Rate Equation:

$$\frac{i}{i_o} = \left(\frac{C_o}{C^*_O}\right)\left[\exp\left(\frac{\alpha nF}{RT}\right)(E - E_{equi}) - \left(\frac{C_R}{C^*_R}\right)\exp\left(\frac{(1-\alpha)nF}{RT}\right)(E - E_{ref})\right]$$

Tafel: $\eta = a + b\log(i)$ **Ch. Tr. Impedance:** $\frac{\partial \eta}{\partial i} = \frac{b}{i}$

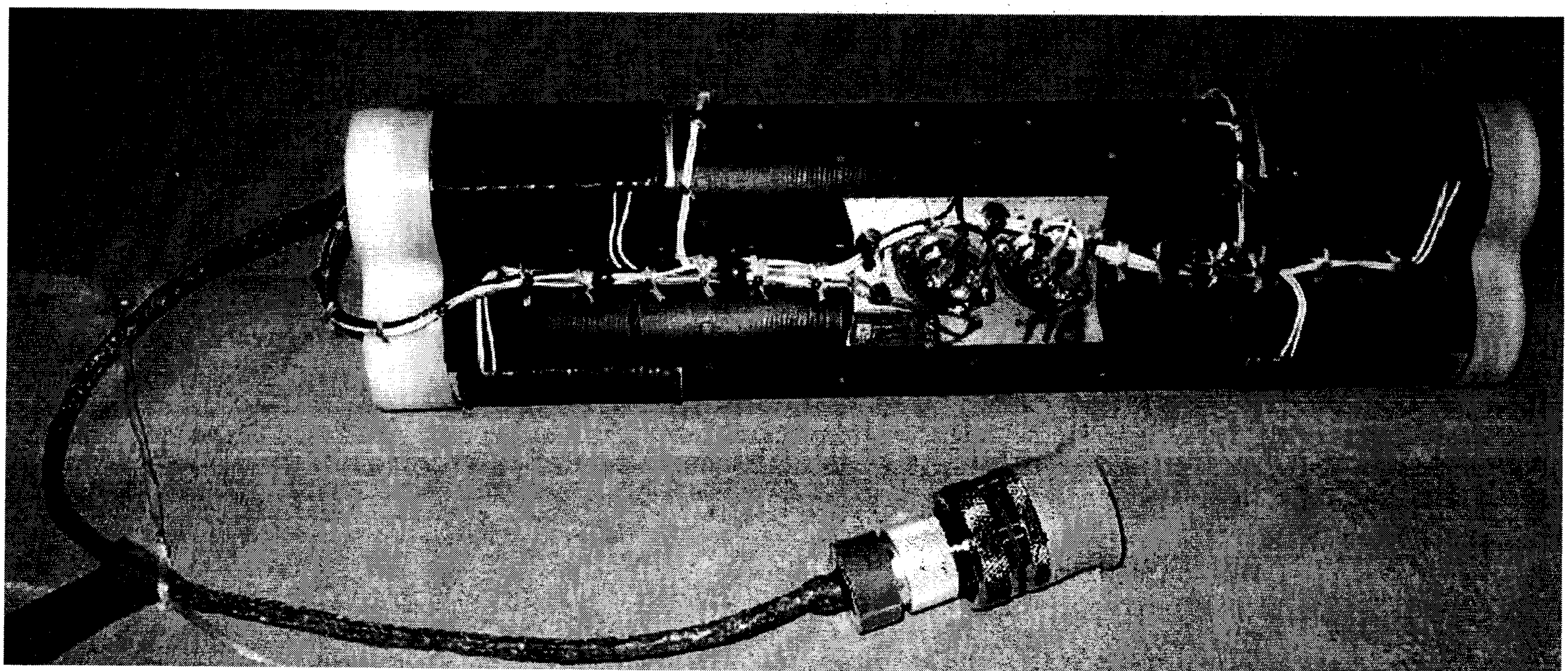
Charge Transfer impedance decreases with increasing current, with SOC (minimum at 50%)

2) Mass Transfer :

- **Expressed as the pre-exponential term in the rate equation**
- **Increases with current and time (as concentration gradients grow).**

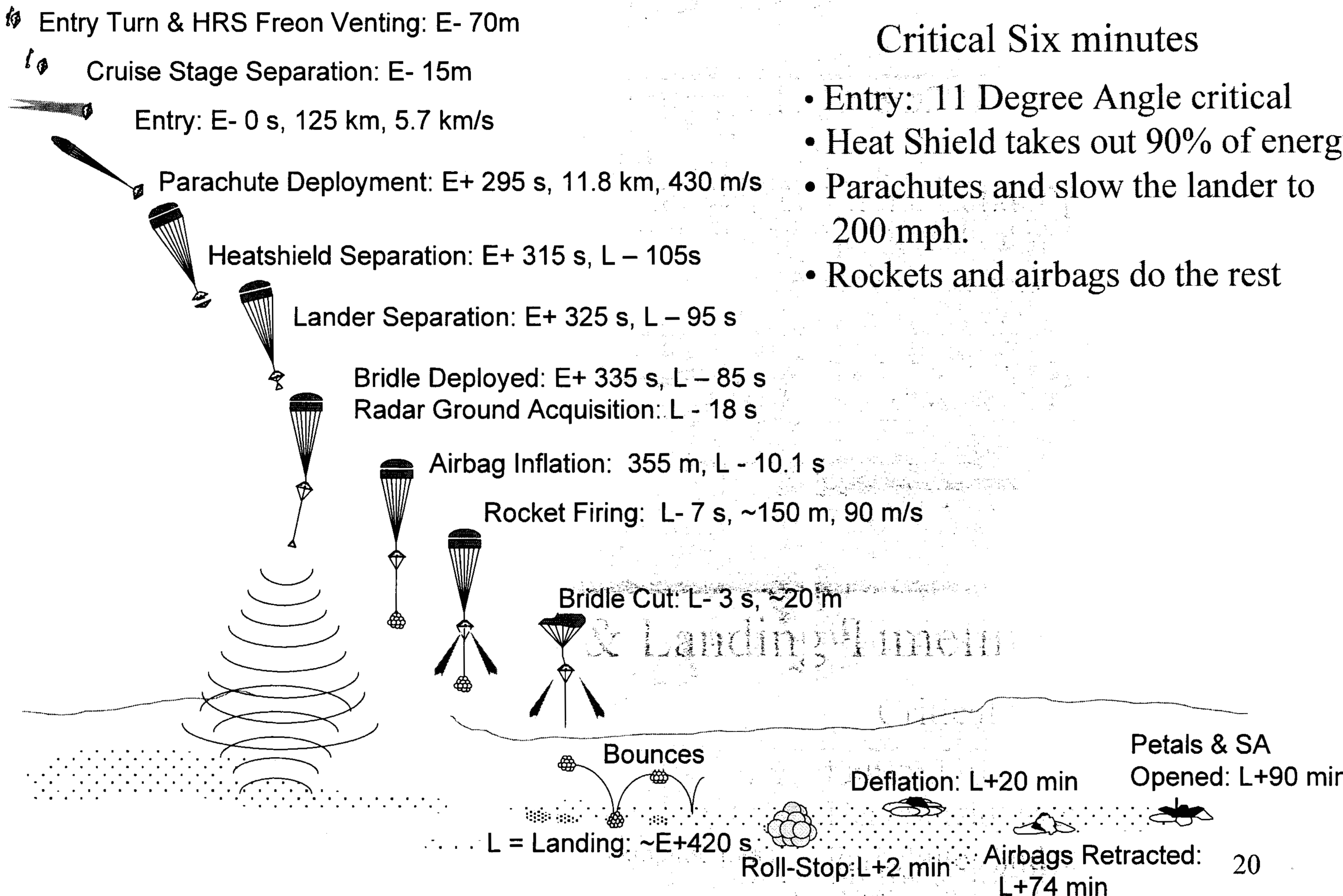
Conclusion: Impedance measurements need to be made at the relevant conditions

Lander $Li\text{-}SO_2$ Battery for EDL



- $Li\text{-}SO_2$ Primary Battery (SAFT) (with 12 Li-SO2 'D' (SX) cells: 36 V, 7 Ah) for MER.
- Five batteries connected in parallel located on the Lander petals.

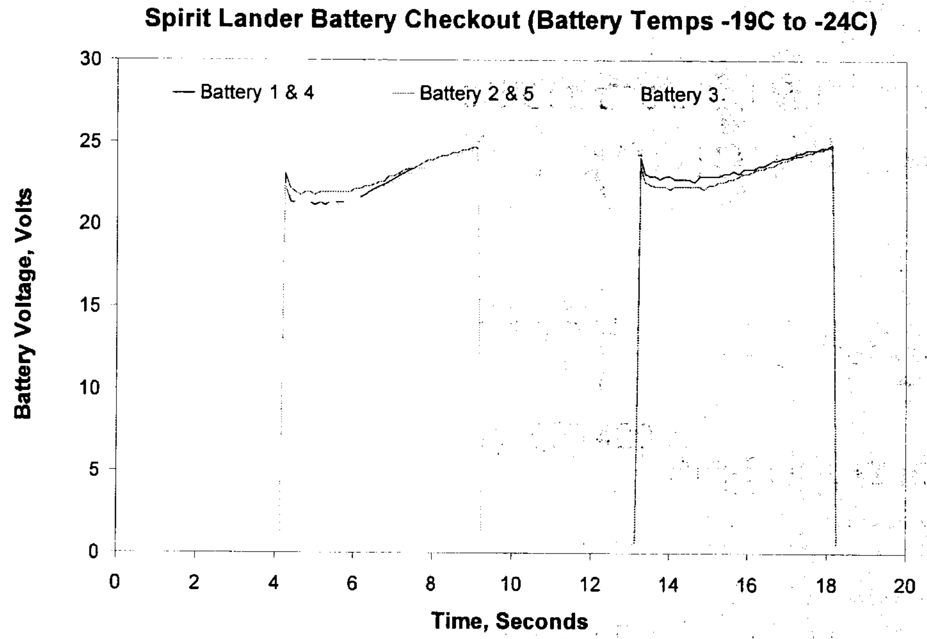
Entry, Descent & Landing Timeline



Critical Six minutes

- Entry: 11 Degree Angle critical
- Heat Shield takes out 90% of energy
- Parachutes and slow the lander to 200 mph.
- Rockets and airbags do the rest

The Problem MER Lander ($Li\text{-}SO_2$) Battery- Health Check



Discharge at 120 Ohms for 5 S

- Based on the baseline plan, the lander batteries will be on bus just before the Turn to Entry (TTE), when the solar array starts spinning away from Sun.
- A voltage undershoot from the LBA ~~might result in a collapse~~ of solar array.
- Two critical voltages are 22 V, below which the POR (Power Off Reset) occurs, and 26 V, below which the Rover battery will be brought onto bus, depleting it during EDL and resulting in inadequate energy for the immediate surface operations.
- Minimum LBAT voltage should therefore above 26 V, or about 2.3 V/cell.
  - The usual cut-off voltage for $Li\text{-}SO_2$ batteries is 2.0 V/cell either for voltage delay or discharge measurements.

Depassivation at Different Shunt Voltages

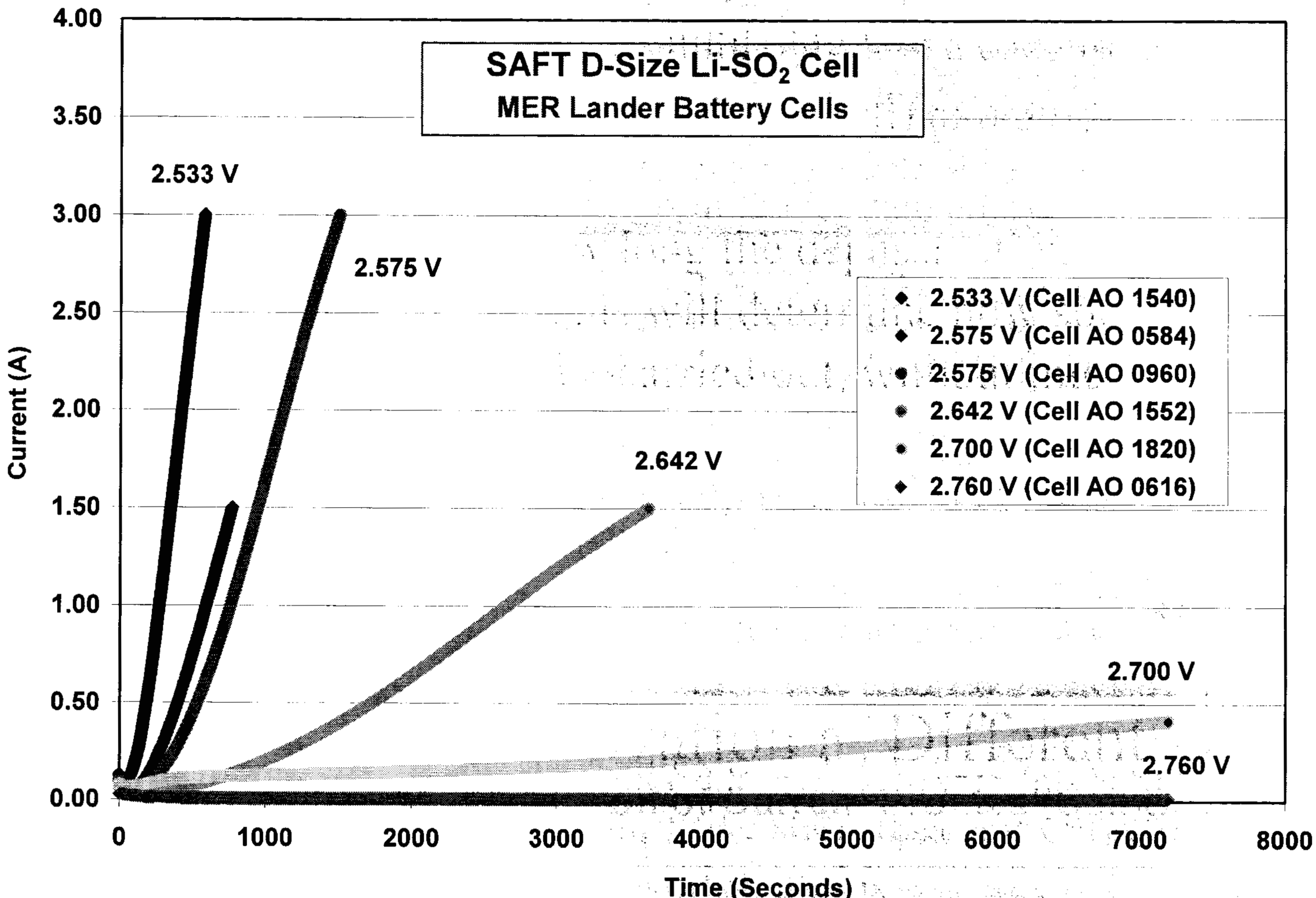
Conclusions from the Initial Screening Studies

(Group II and III)

- The Li-SO_2 cells can be adequately depassivated via constant potential discharge.
- High shunt voltages of 34 V (2.833 V/cell) and 33.12 V (2.760 V/cell) do not provide adequate depassivation.
- On the other hand, low shunt voltages of 30.9 V (2.575 V/cell) and 30.4 V (2.533 V/cell) depassivate quite rapidly, such that the currents are significantly high and saturate the shunt stages.
- Optimum shunt voltages are 32.4 V (2.7 V/cell) and 31.7 V (2.642 V/cell), which will be examined further.
- It was decided to determine how long the depassivation effects could last, before depassivation sets in. This will determine how soon (6-36 h) before TTE) the depassivation could be carried out, without interfering with the EDL.

Comparison of Depassivation at Different voltages

Depassivation at 0°C- Comparison of Current Profiles (Cell Groups 1-3)



- Lower the voltage, faster will be the depassivation rate.

Depassivation at Different Shunt Voltages

Conclusions from the Group V Cell Tests

- Depassivation at 32.4 V is rather slow and takes several hours to reach sizeable currents, with a significant drain in the capacity.
- Depassivation (even repeated) at a low shunt voltages of 30.9 V (2.575 V/cell) and 30.4 V (2.533 V/cell) for short duration of 6 min is once again inadequate.
- Optimum shunt voltage appears to be 31.7 (2.642 V) for 25 minutes with repetitive depassivation cycles, each of 25 minutes duration, either at 31.7 (2.642) or at 32.4 V (2.7 V/cell), which will be examined in the next set.
- It appears that the depassivation effects hold good until 18 hours.
- The differences in the temperatures of batteries 1-5°C, may cause changes in the depassiavtion rate; Needs to be examined.

Five MER Lander Batteries Test

Summary of the Test Results

Test Time (Seconds)	Test Time (Hours)	Current	Duration (Seconds)	Low Voltage (V)	Ending Current	Ending Capacity
0	0	0		36.3647		
125.148	0.035	Var	1500	31.200	7.5379	1.3792
5263.20	1.462	Var	1500	31.999	5.7578	1.7192
78754.18	21.876	2.50	120	30.1408	2.50	0.0830
78874.18	21.909	5.00	60	30.9648	5.00	0.0830
78934.19	21.926	7.50	240	30.7304	7.50	0.5000
79174.19	21.993	9.00	65.838**	31.1949	12.00	0.1646
82590.34	22.942	2.50	120	31.4287	2.50	0.0830
82710.36	22.975	5.00	60	31.1376	5.00	0.0830
82770.35	22.992	7.50	240	30.9416	7.50	0.5000
83010.35	23.058	9.00	12152.67	31.195	12.00	30.3817
* Total capacity discharged during de-passivation =3.098 Ah (0.620 Ah/battery)						
** Power surge (most likely) prematurely terminated test (test restarted from step 7)						
Total Capacity Discharged From Batteries = 34.977 Ah						

1st Depassivation at: 31.200 V (System Voltage)

- Duration of step = 25 min
- Ending Capacity = 1.379 Ah
- Ending Current = 7.538 Amps

2nd Depassivation at 32.000 V (System Voltage)

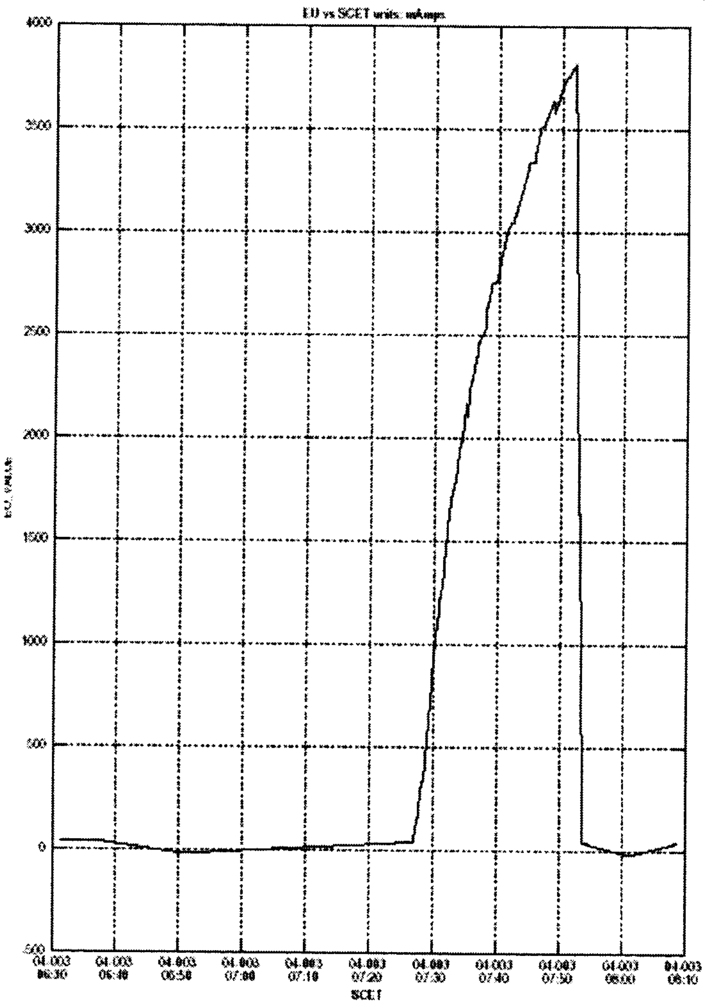
- Duration of step = 25 min
- Ending Capacity = 1.719 Ah
- Ending Current = 5.758 Amps

Constant current discharge (after 20 hour OCV)

- Lowest voltage @ 2.50 A = 30.1408 V
- Lowest voltage @ 5.00 A = 30.9648 V
- Lowest voltage @ 7.50 A = 30.7304 V
- Lowest voltage @ 9.00 A = 31.1949 V

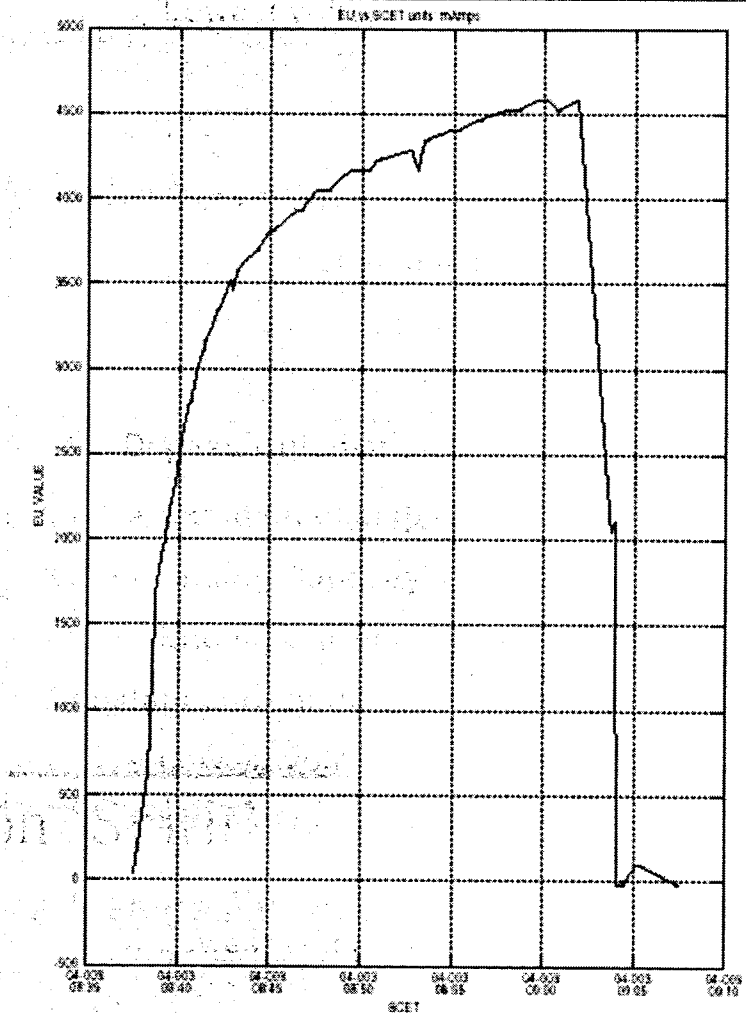
Depassivation on 'Spirit'

1st Depassivation at 31.2 for 25 min



Max Current: 3.75 A

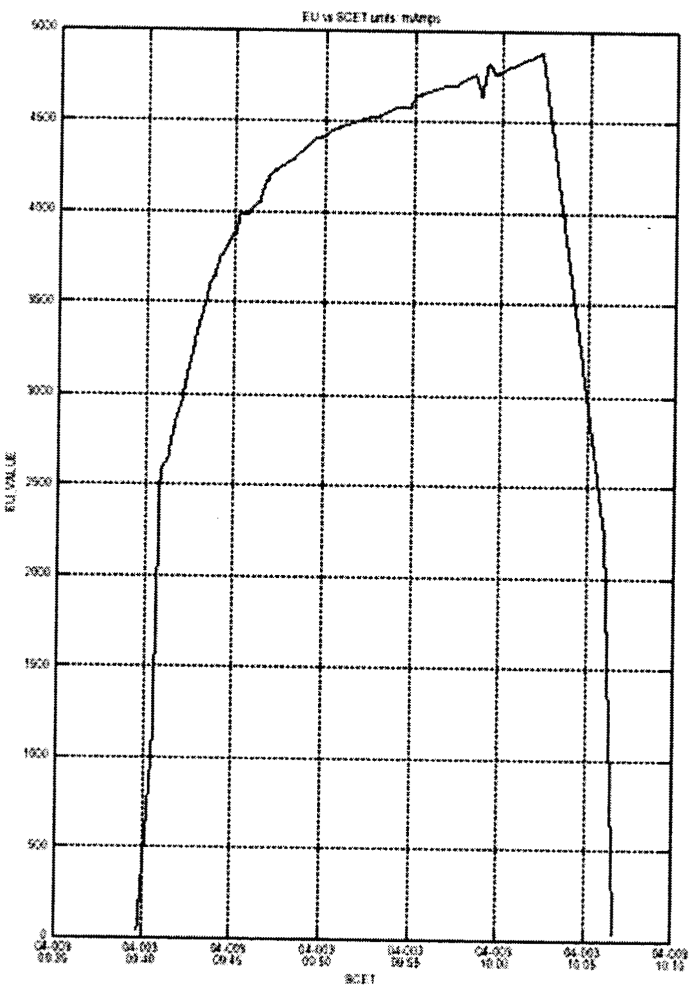
2nd Depassivation at 31.2 for 25 min



Max Current: 4.578 A

Depassivation on 'Spirit'

3rd Depassivation at 31.2 for 25 min

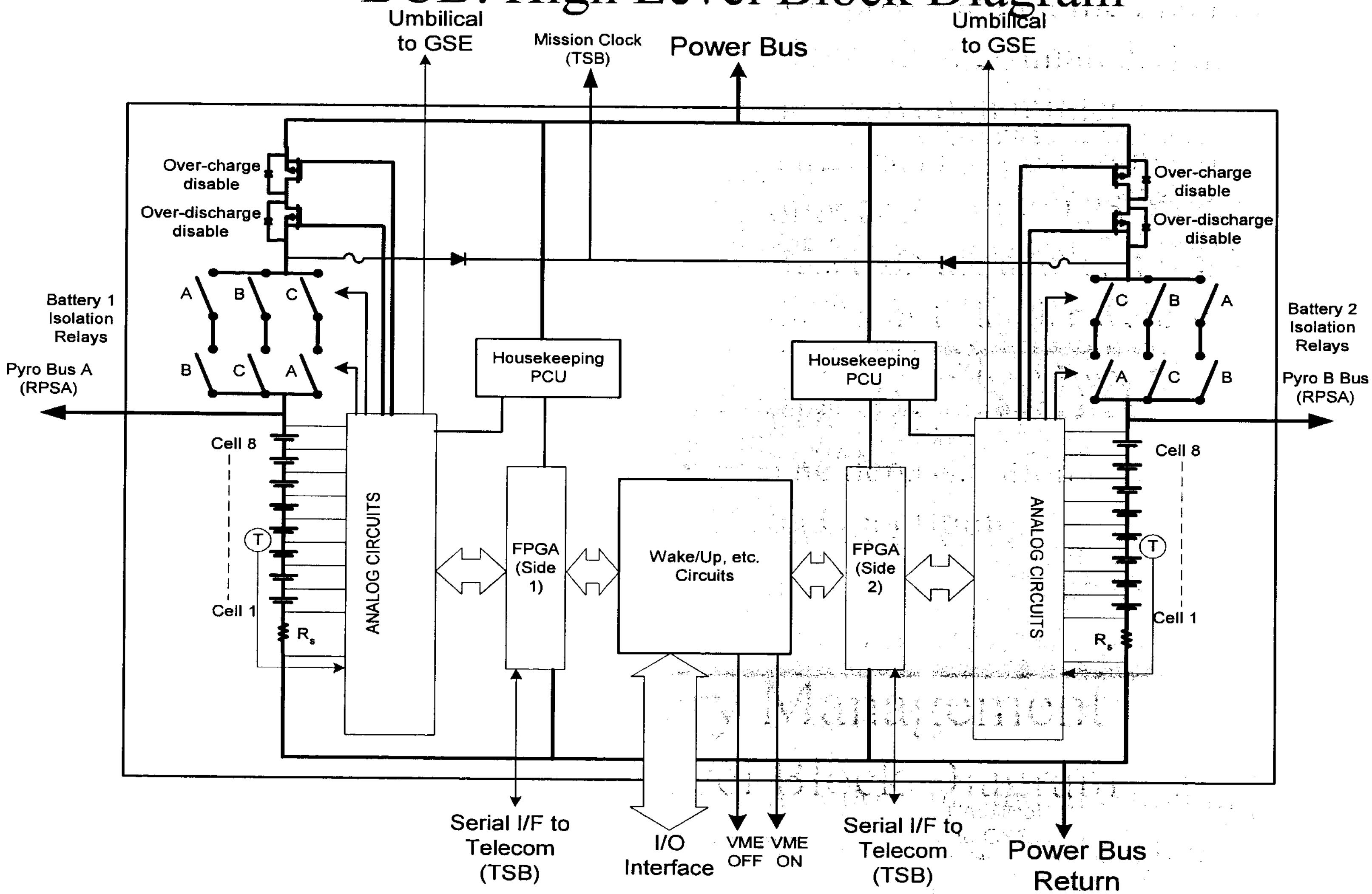


Max Current: 4.87 A

- The observed battery currents are lower than what would be expected from the laboratory tests on cells, strings and five battery tests at a depassivation voltage of 31.2 V.
- It is possible that the line impedance is higher than estimated, thus making the depassivation milder.
- The LBAT report shows healthy voltage of over 33 V (at 0.25 A).
- Based on the above, it was concluded that the "Spirit" lander were sufficiently depassivated, as was confirmed from the EDL data.
- The depassivation profiles were identical on Opportunity

Rover Battery Management

BCB: High Level Block Diagram



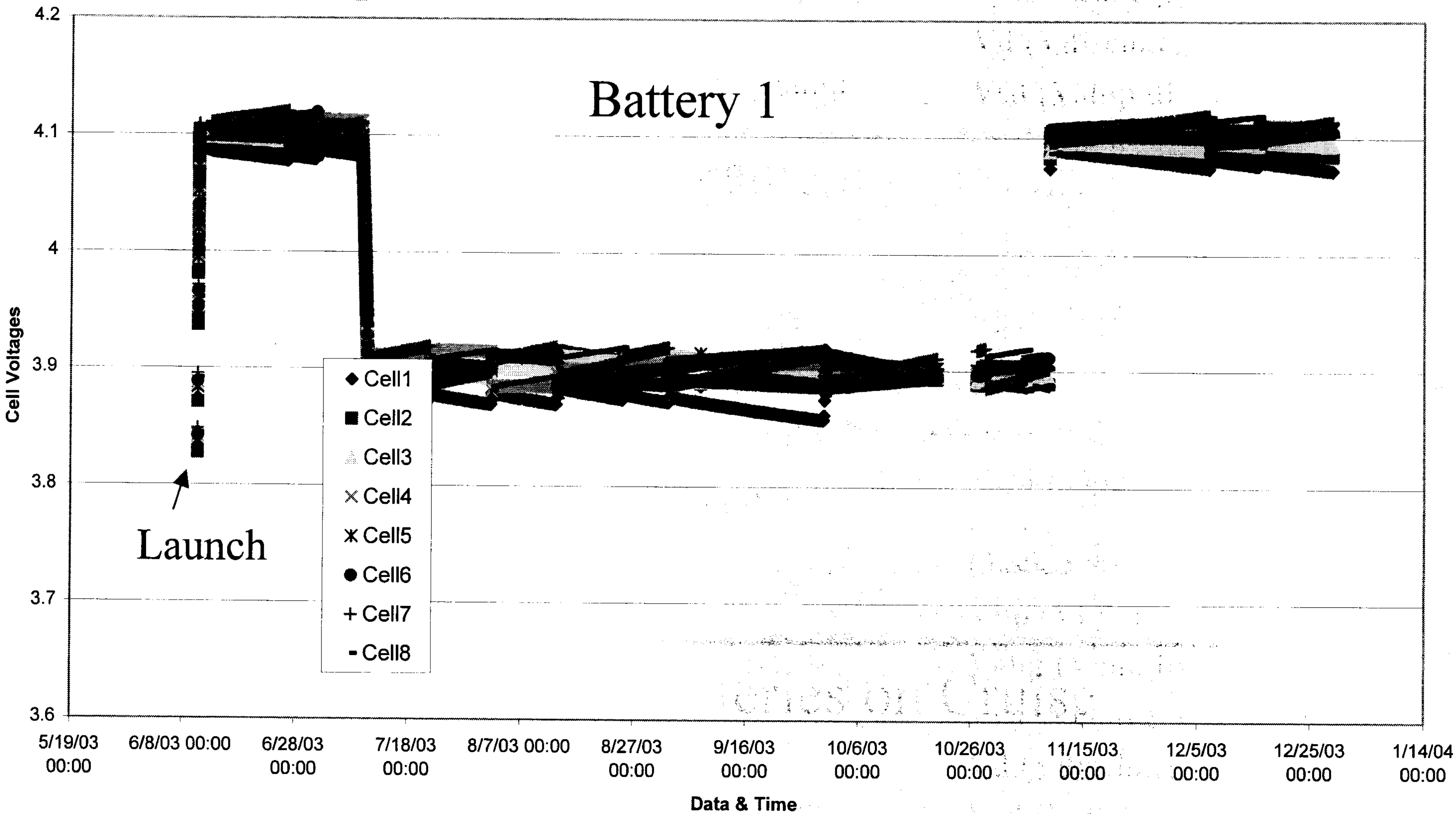
- **Individual cell voltage monitor and control with bypass.**
- **Each battery controlled separately**

Battery Management Protocol

- Charge control
  - Stop Charge (open charge FET) if:
    - Any cell is greater than or equal to Vcmd
    - All cells are above Vbp
    - Charge rate is greater than 1C
    - Any cell is <1V and the battery is >20V.
  - Start Charge (close charge FET) if:
    - All cells are below Vch
    - After POR
  - Stop Discharge (open discharge FET) if:
    - Any cell is less than or equal to Vsd
    - Discharge rate exceeds 2C (latchoff, ground only)
  - Start Discharge (close discharge FET) if:
    - All cells are above Vd.
- Charge Balancing
  - Start cell bypassing at or above Vbp
  - Stop cell bypassing at or below Vebp

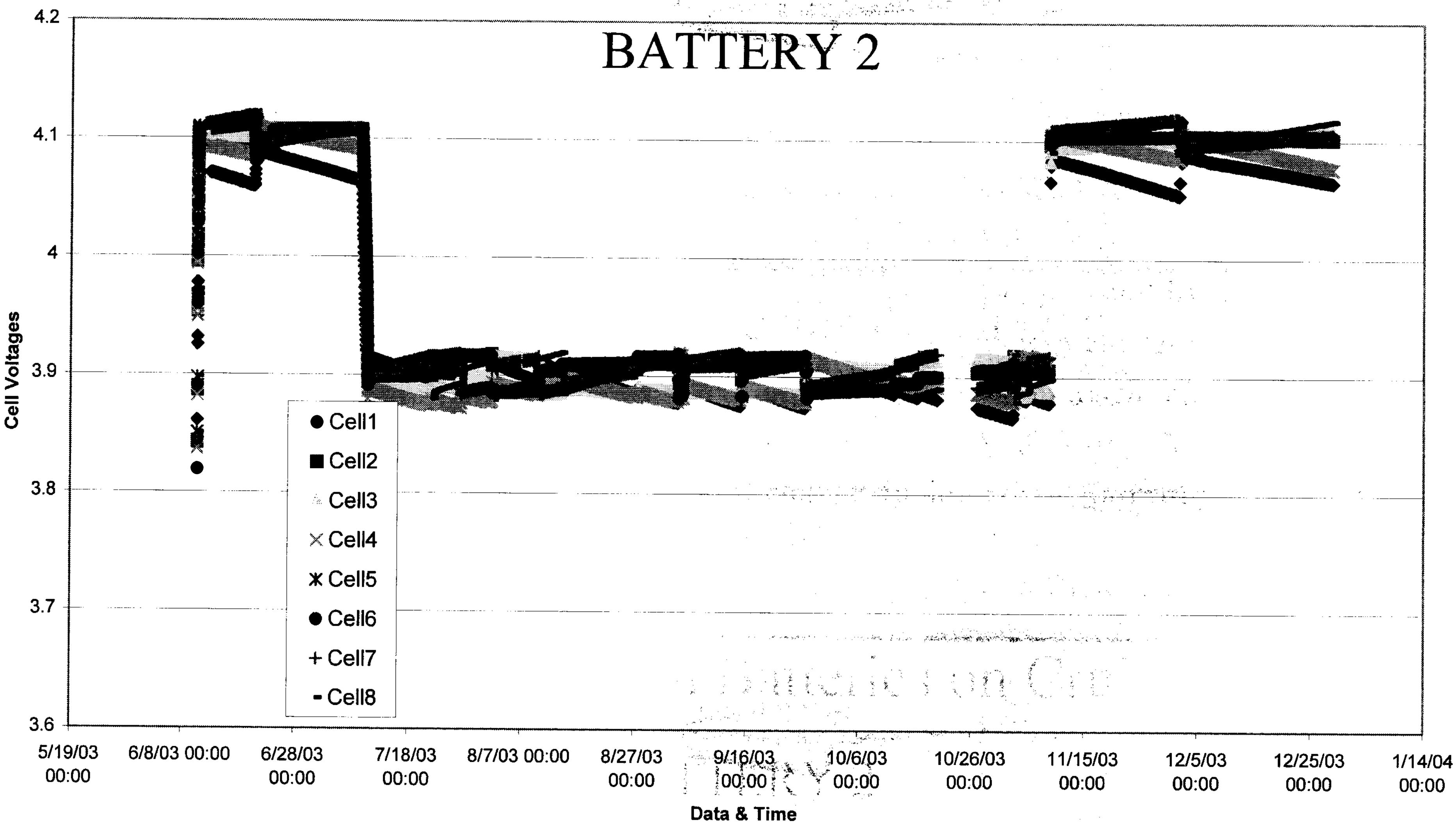
- Terminology Definitions
  - Vcmd (Vcommand)= Vsc (Vstop charge) = one of four prog levels (3.85, 3.95, 4.15, 4.20V)
  - Vbp (Vbypass) = Vcmd - 30mV
  - Vebp (Vend bypass) = Vcmd -70mV
  - Vch (Vcharge) = Vcmd - 150mV
  - Vd (Vdischarge) = 3.4V
  - Vsd (Vstop discharge) = 2.9V

Spirit Li Ion Batteries on Cruise



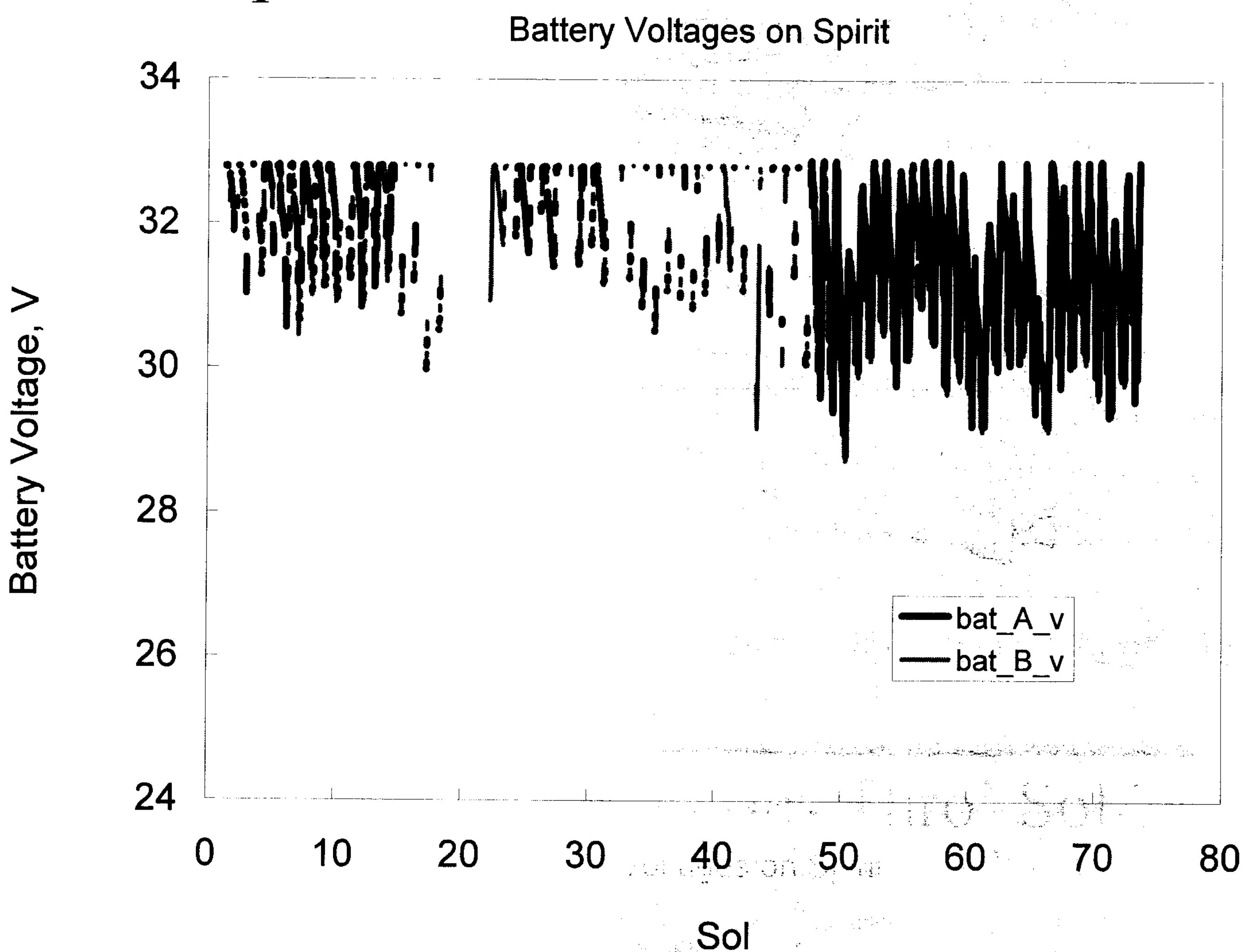
- ~ 25% discharge during launch. 80% state of charge during cruise and fully charged before landing.
- Cells periodically balanced via bypass, if the cell divergence is sufficiently large.

Spirit Li Ion Batteries on Cruise



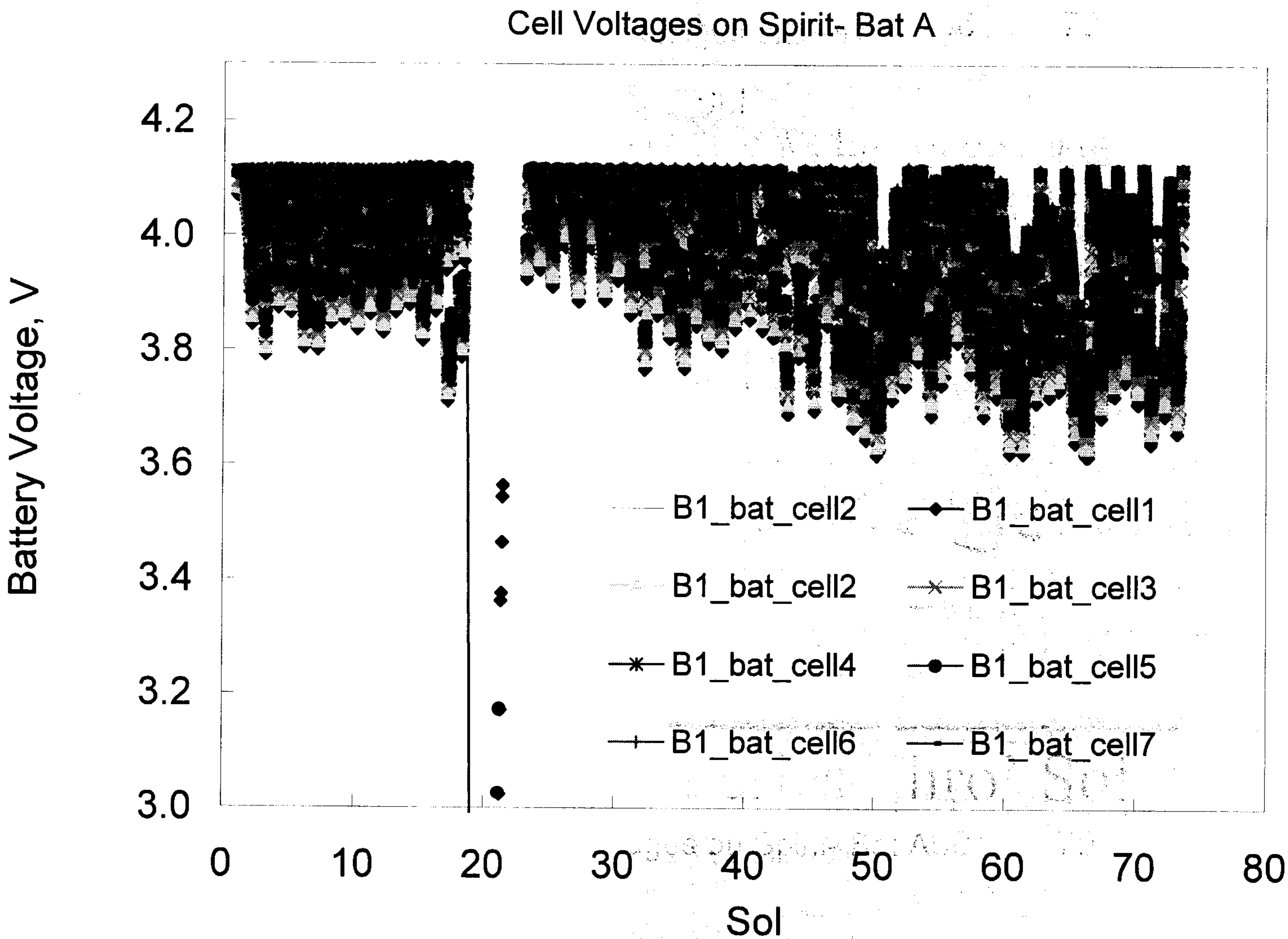
- **Behavior of battery 2 is similar to battery 1**
- **Similar behavior of Opportunity as well.**

Spirit Li Ion Batteries Thro' Sol 74

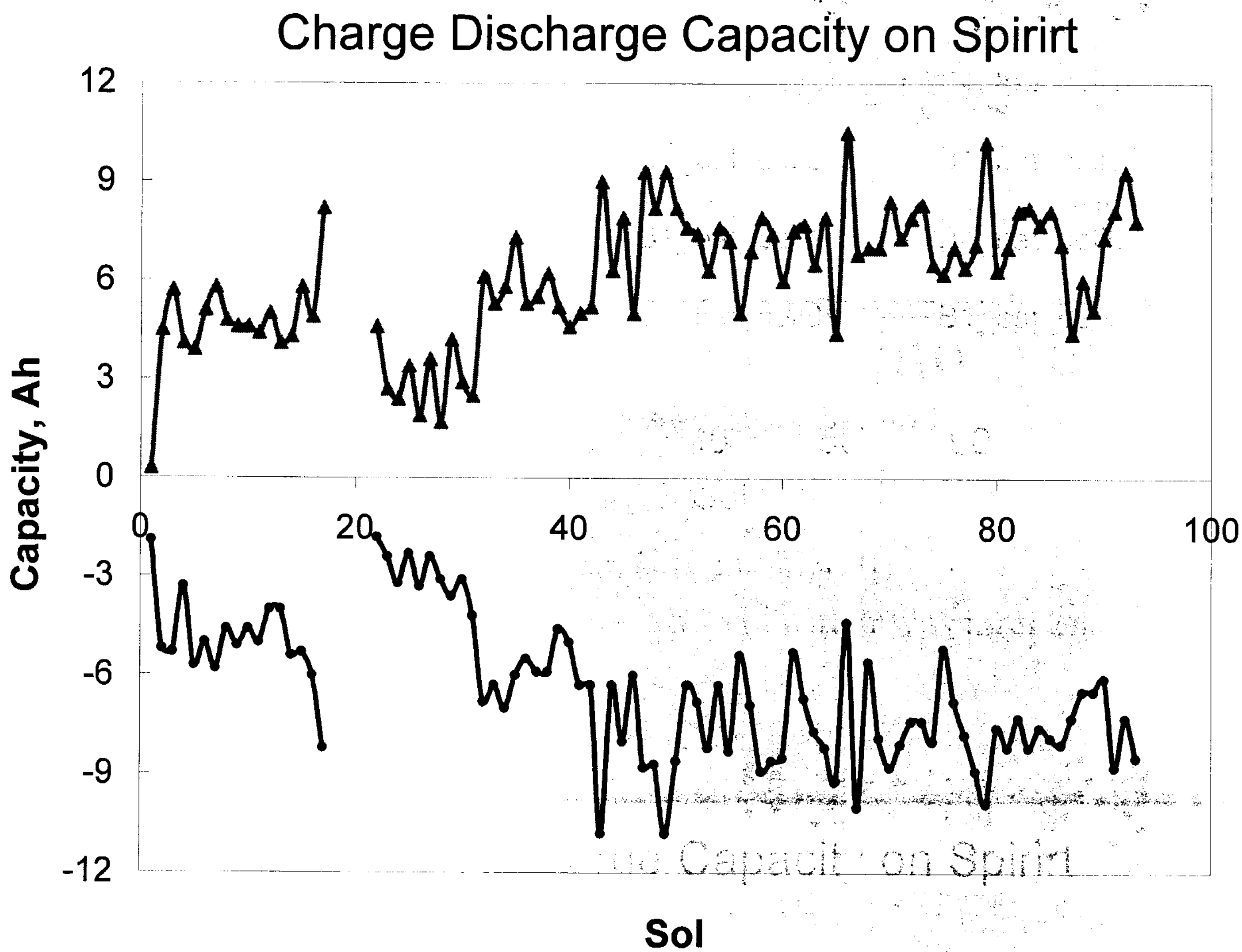


- Battery End of discharge voltage: 30.5 V; End of discharge voltages are a little bit higher in the second week.
- Both batteries have nearly identical voltages

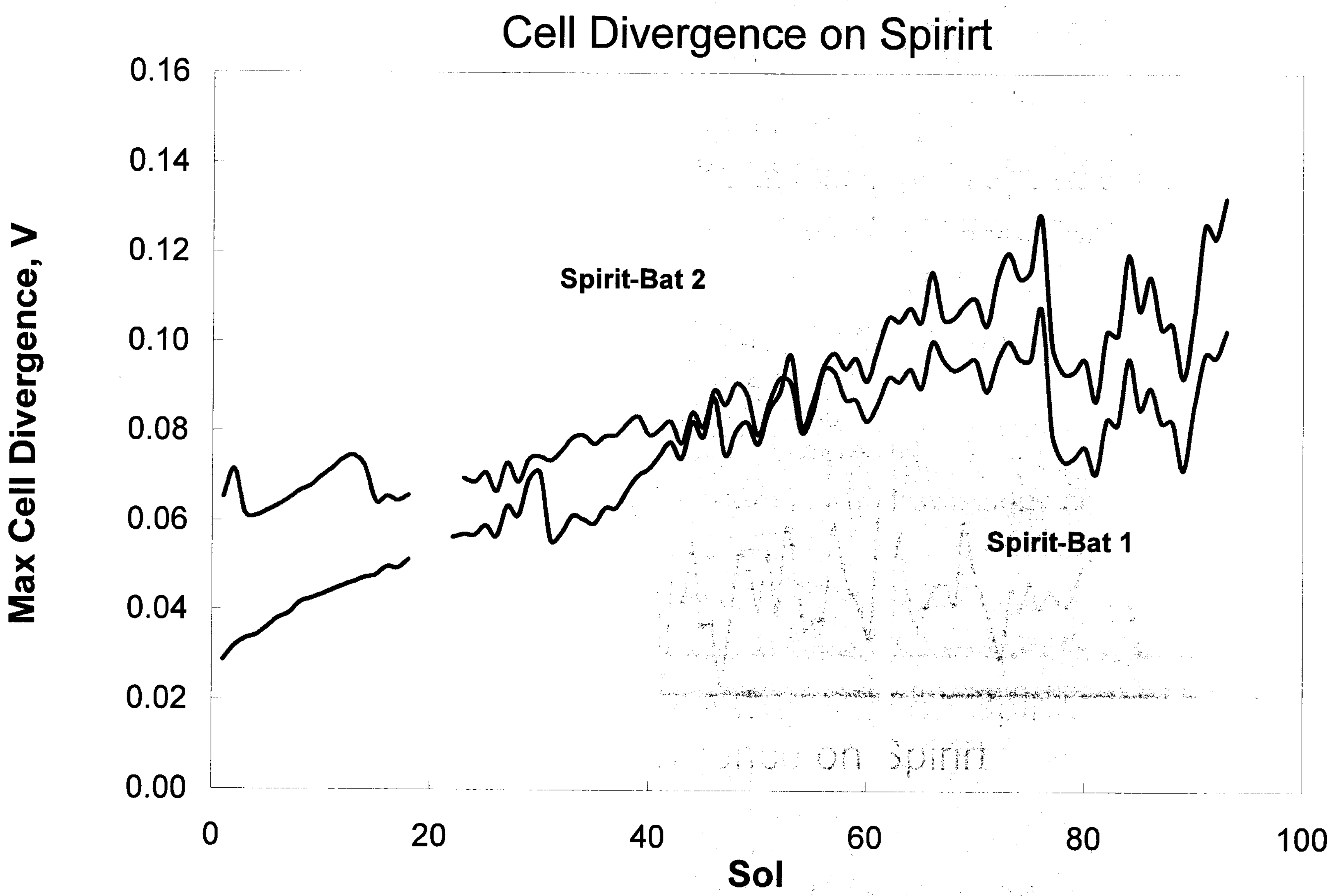
Spirit Li Ion Batteries Thro' Sol 74



- **Typical minimum cell voltage : 3.6 V (~ 50%DOD)**
- **Spirit anomaly attributed to flash memory, which was later erased.**
- **Batteries experienced a fairly deep discharge.**

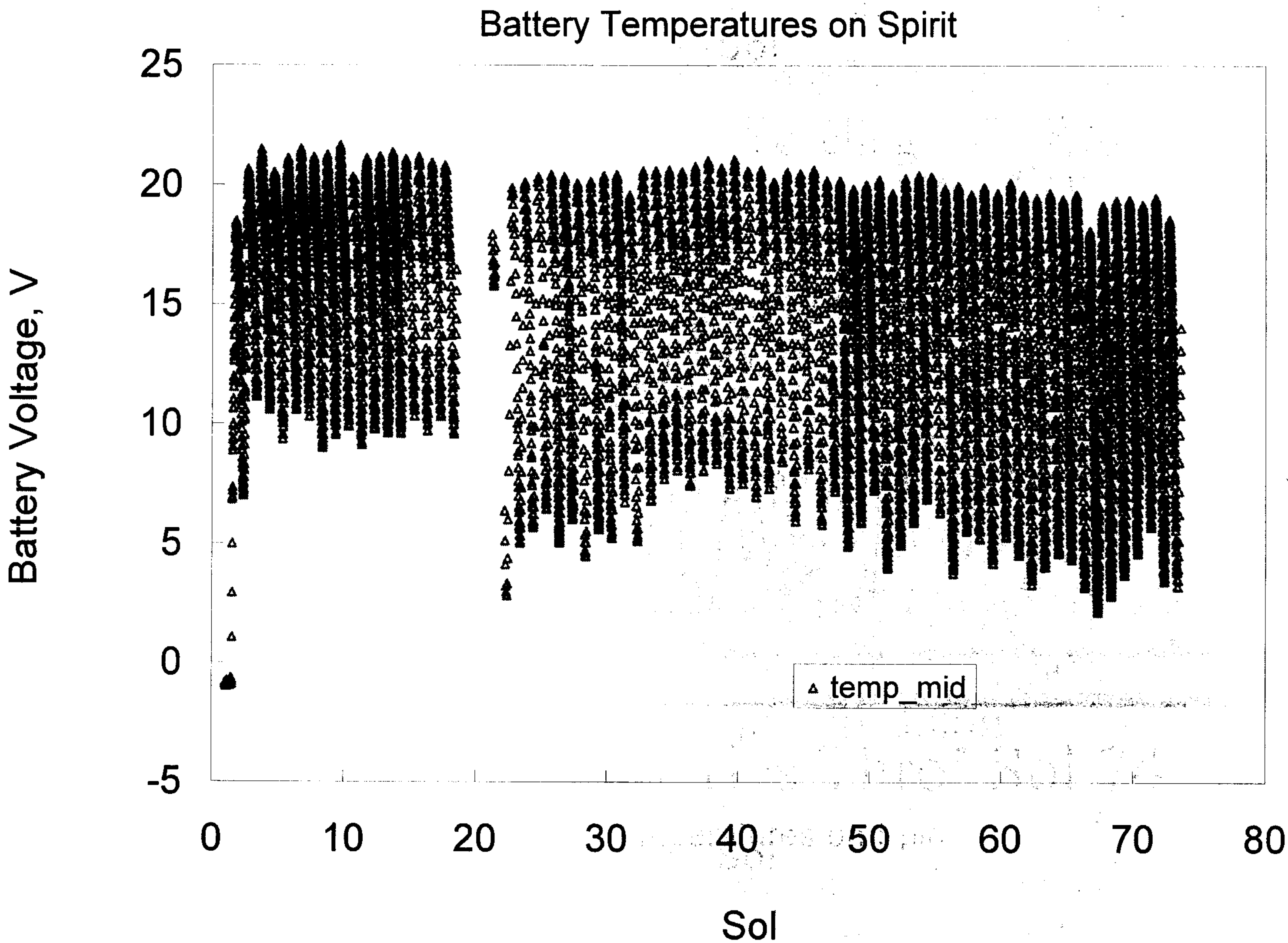


- Depth of discharge is typically 60-70%.
- Max discharge current is 1.4 A and the typical charge current is ~1 A.
- C/D ratio is close to one.



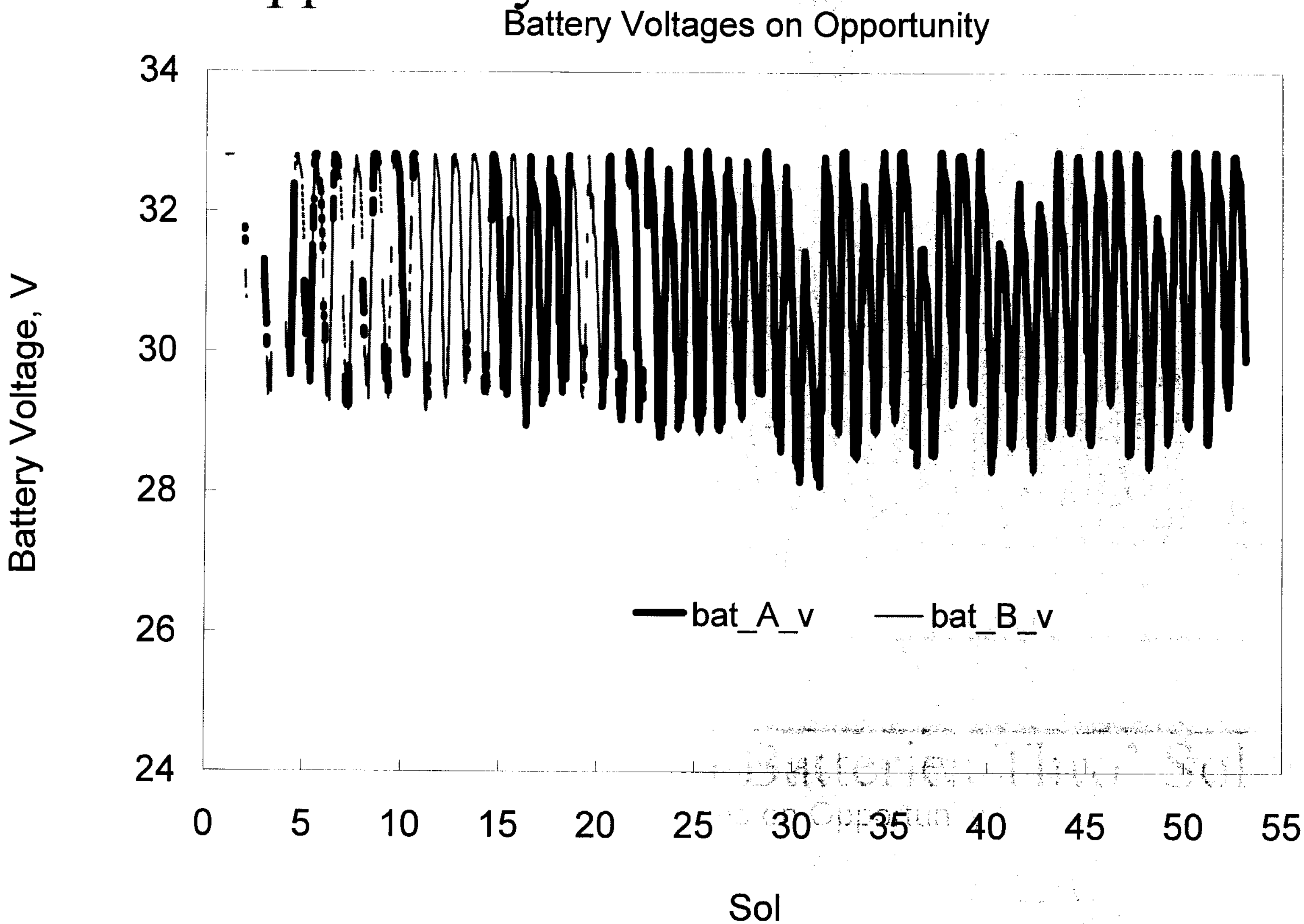
- Cell divergence increasing upon cycling.

Spirit Li Ion Batteries Thro' Sol 74



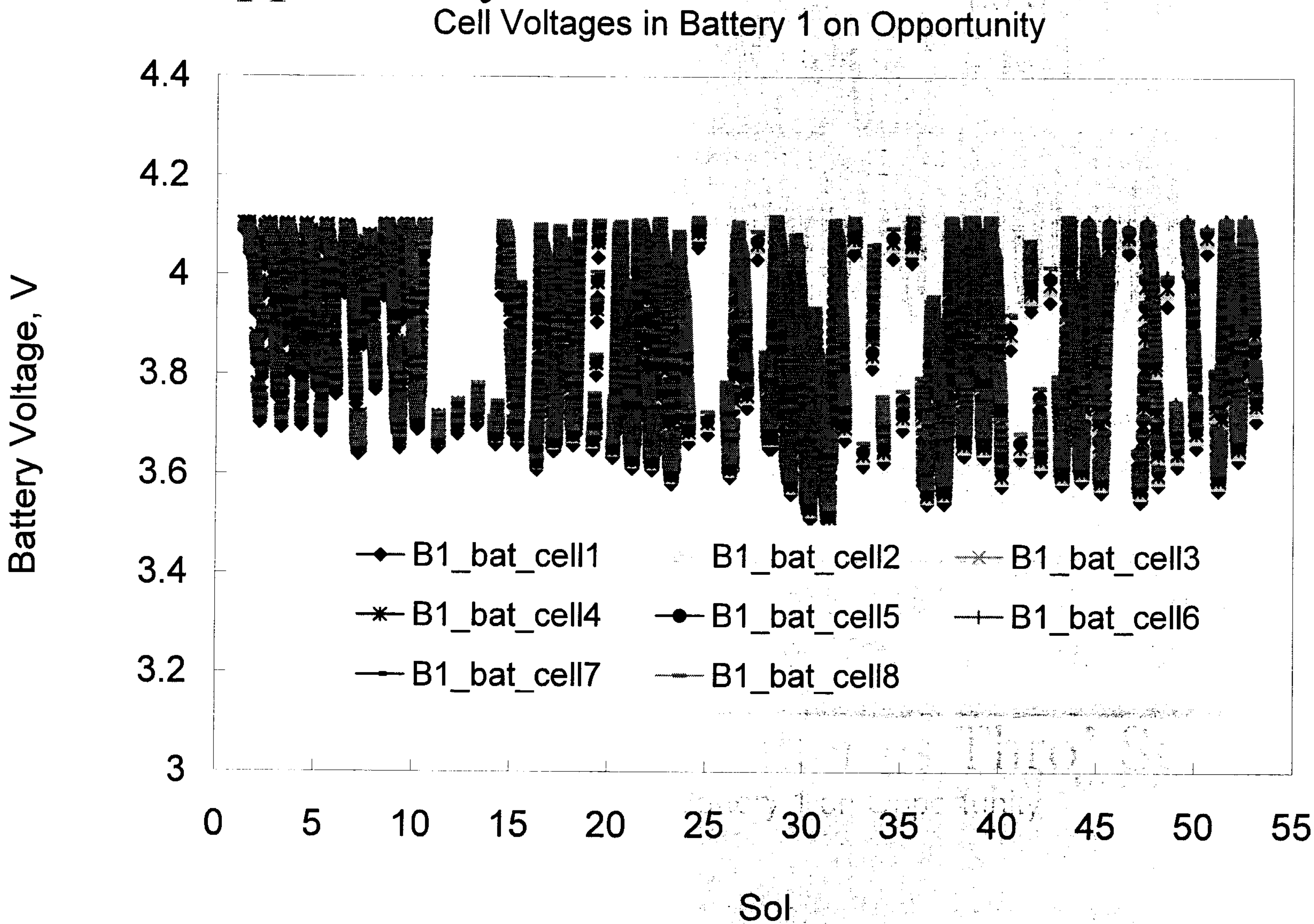
- Battery temperatures are ranging from + 5 to 22°C.
- About 10°C warmer than anticipated.

Opportunity Li Ion Batteries Thro' Sol 54

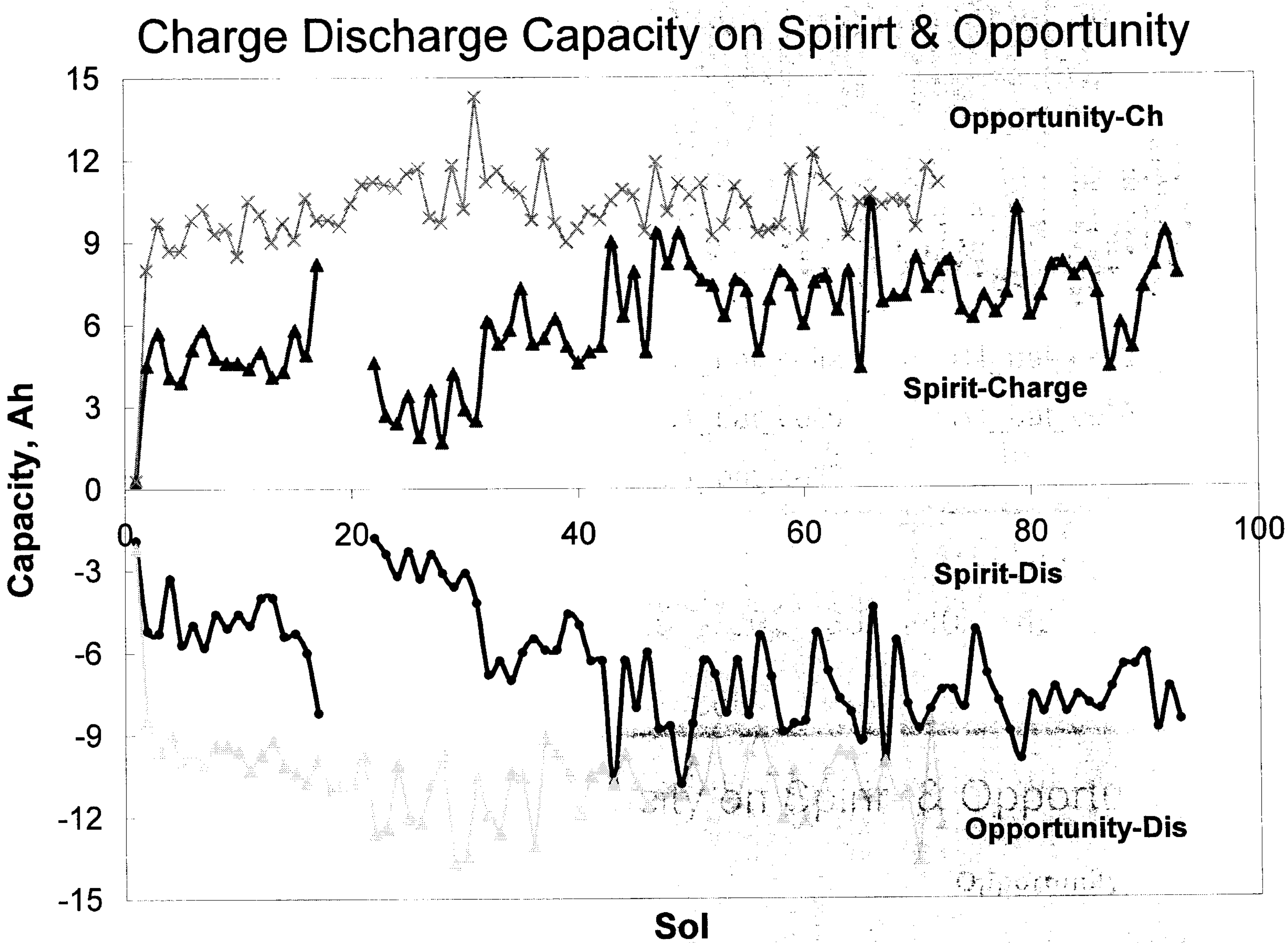


- Battery End of discharge voltage: 28 V; End of discharge voltages are a little bit lower than in the case of Spirit.
- Both batteries have nearly identical voltages.

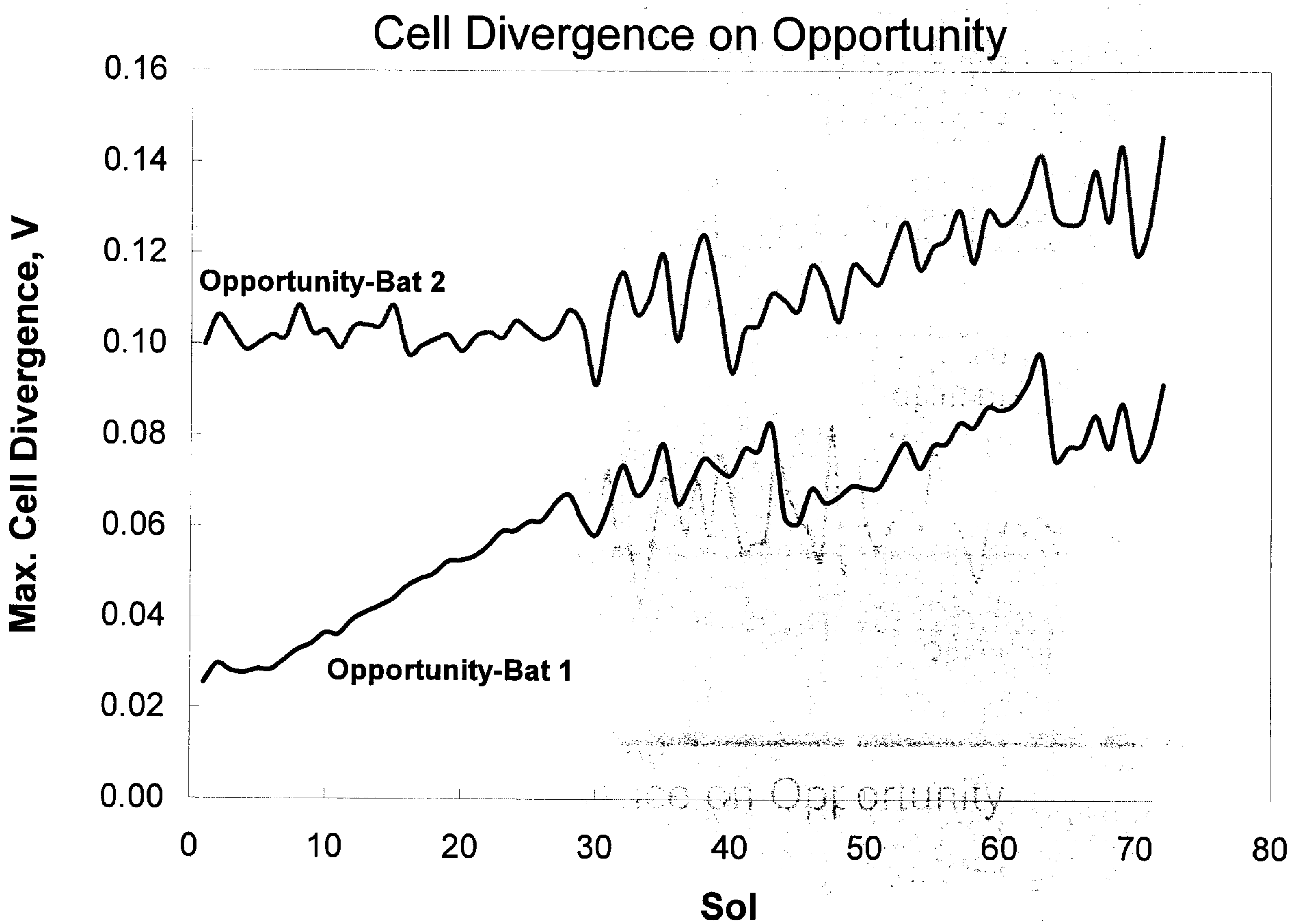
Opportunity Li Ion Batteries Thro' Sol 54



- Typical minimum cell voltage : 3.55 V, about 50 mV lower than on Spirit

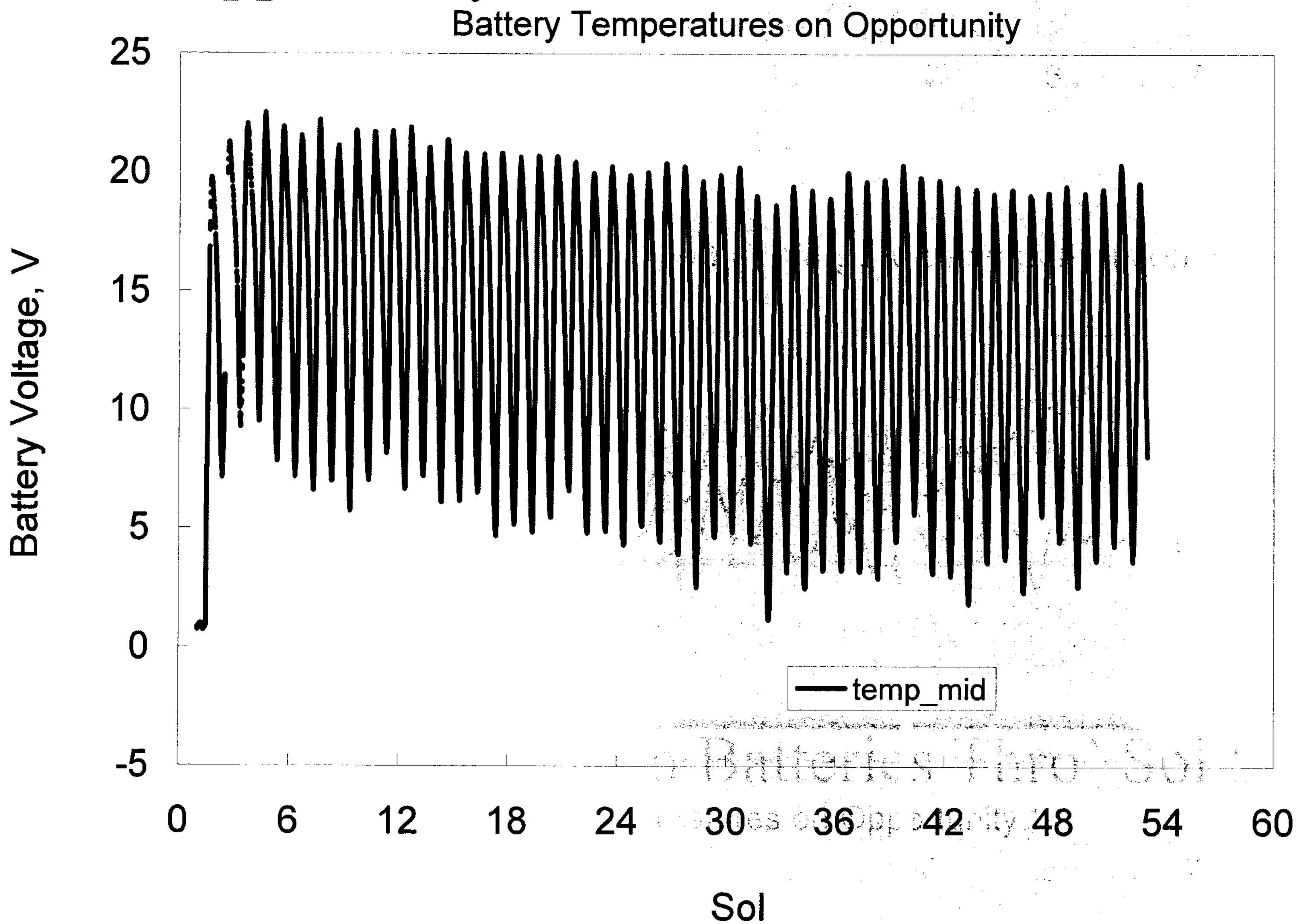


- Max discharge current is 1.6 A and the typical charge current is ~1 A.
- Higher DOD on Opportunity, compared to Spirit



- Cell divergence increasing upon cycling, to the extent as on Spirit.

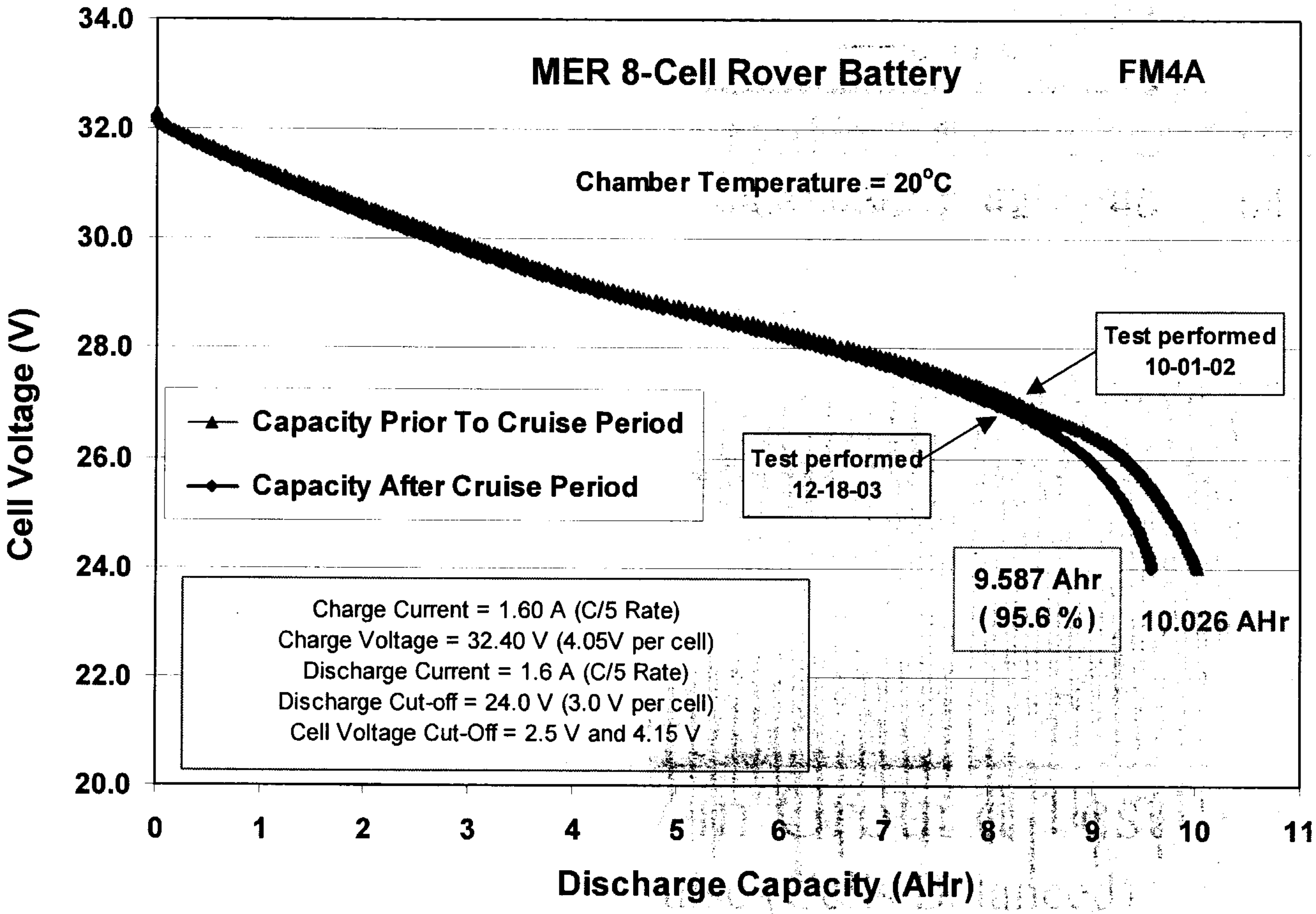
Opportunity Li Ion Batteries Thro' Sol 54



- Battery temperatures are about 1-2°C lower than on the Spirit, but about 10°C warmer than anticipated.

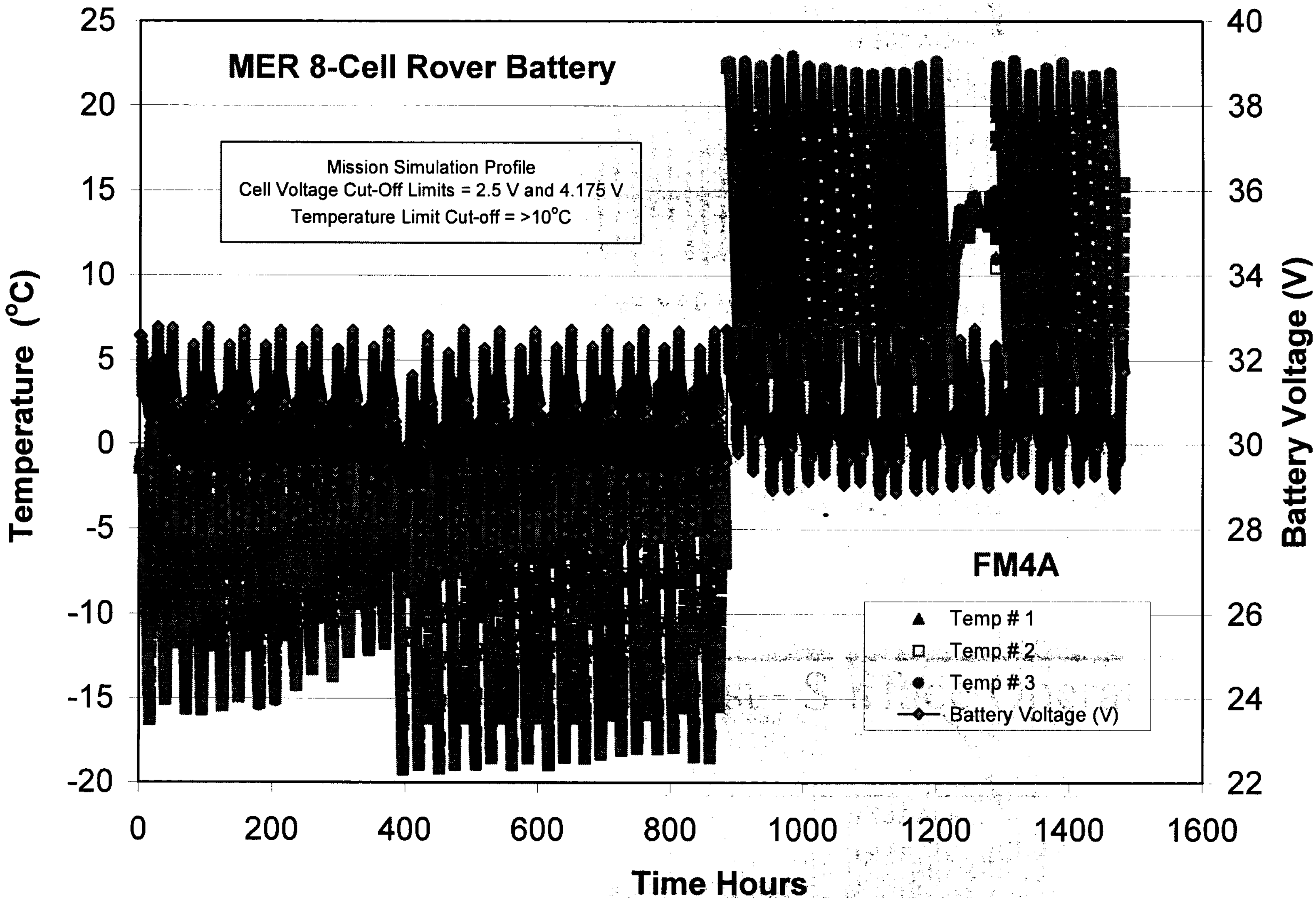
Rover Battery in Ground Test

Capacity After Cruise (Cells Balanced)



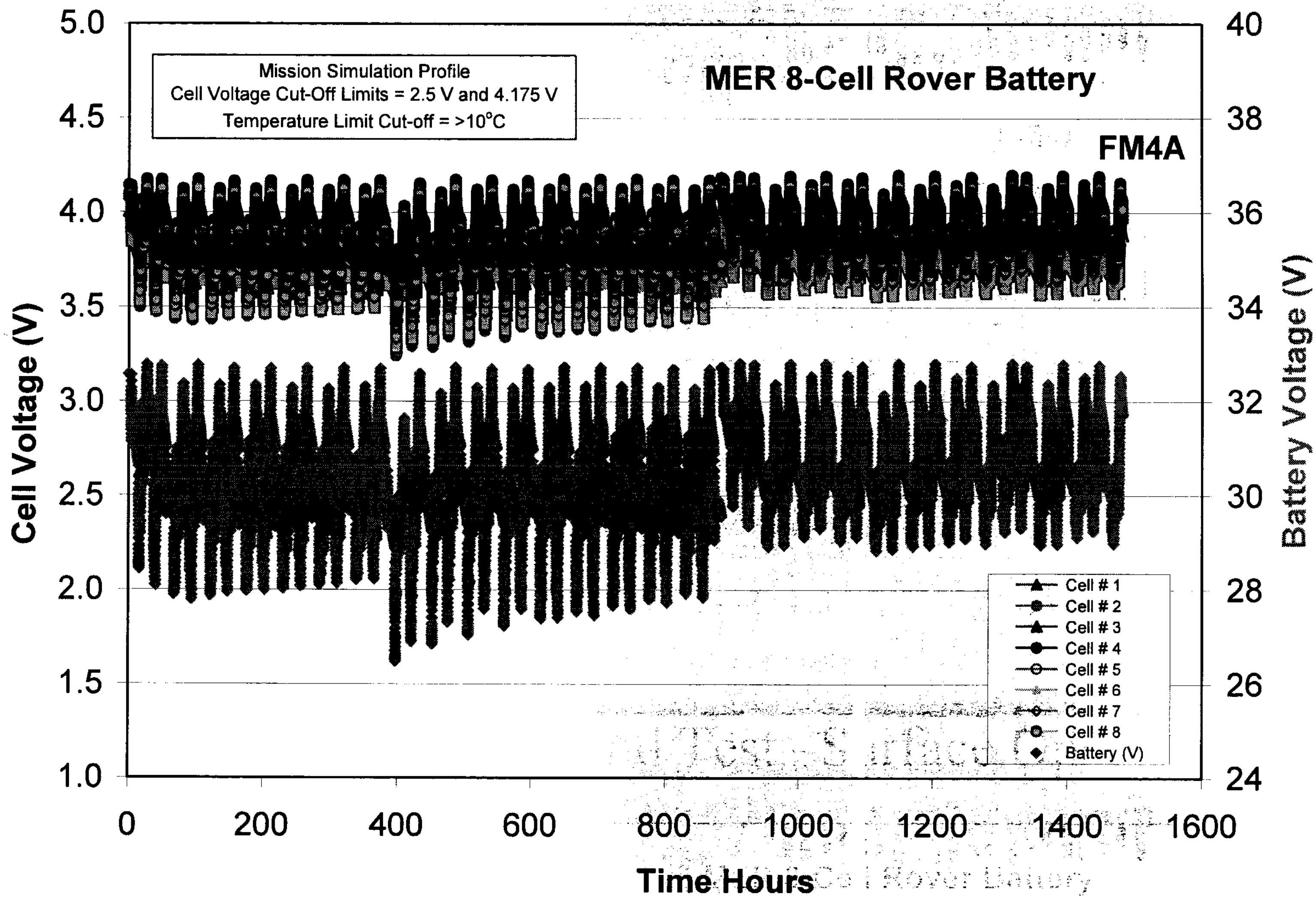
- After cell balance, discharge terminated by battery voltage (Min. Cell Voltage: 2.518 V).
- Over 97 % of capacity retained during ATLO and cruise; About 7 Ah capacity at –20°C.

Rover Battery in Ground Test– Surface Operation



- Temperature adjusted mid-course, based on telemetry data.
- Characterization tests followed after 90 sols

Rover Battery in Ground Test– Surface Operation

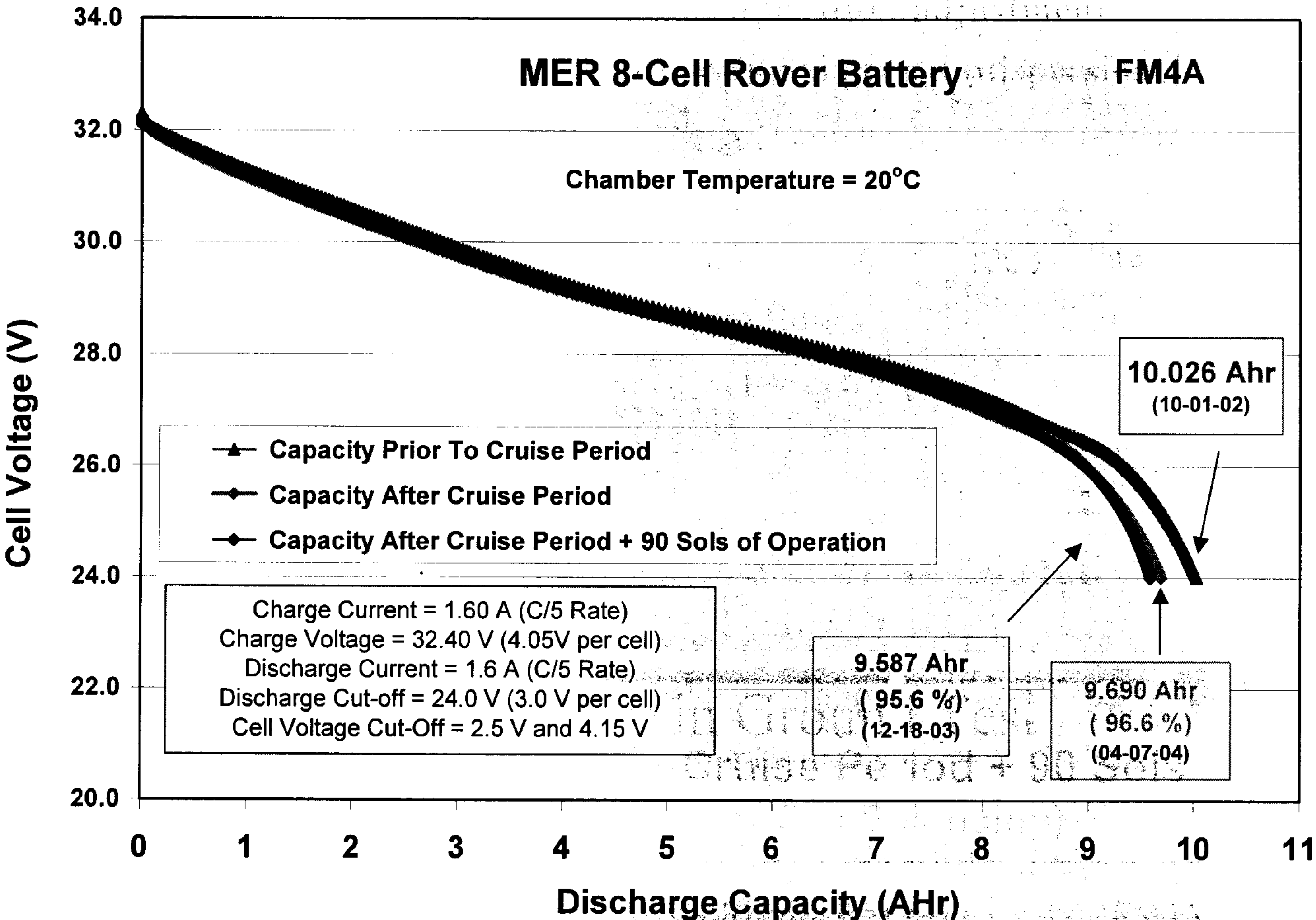


- **High cell and battery voltages after temperature adjustment.**
- **Cells were not balanced during entire 90 Sol period (dispersion = ~ 175 mV)**

Rover Battery in Ground Test

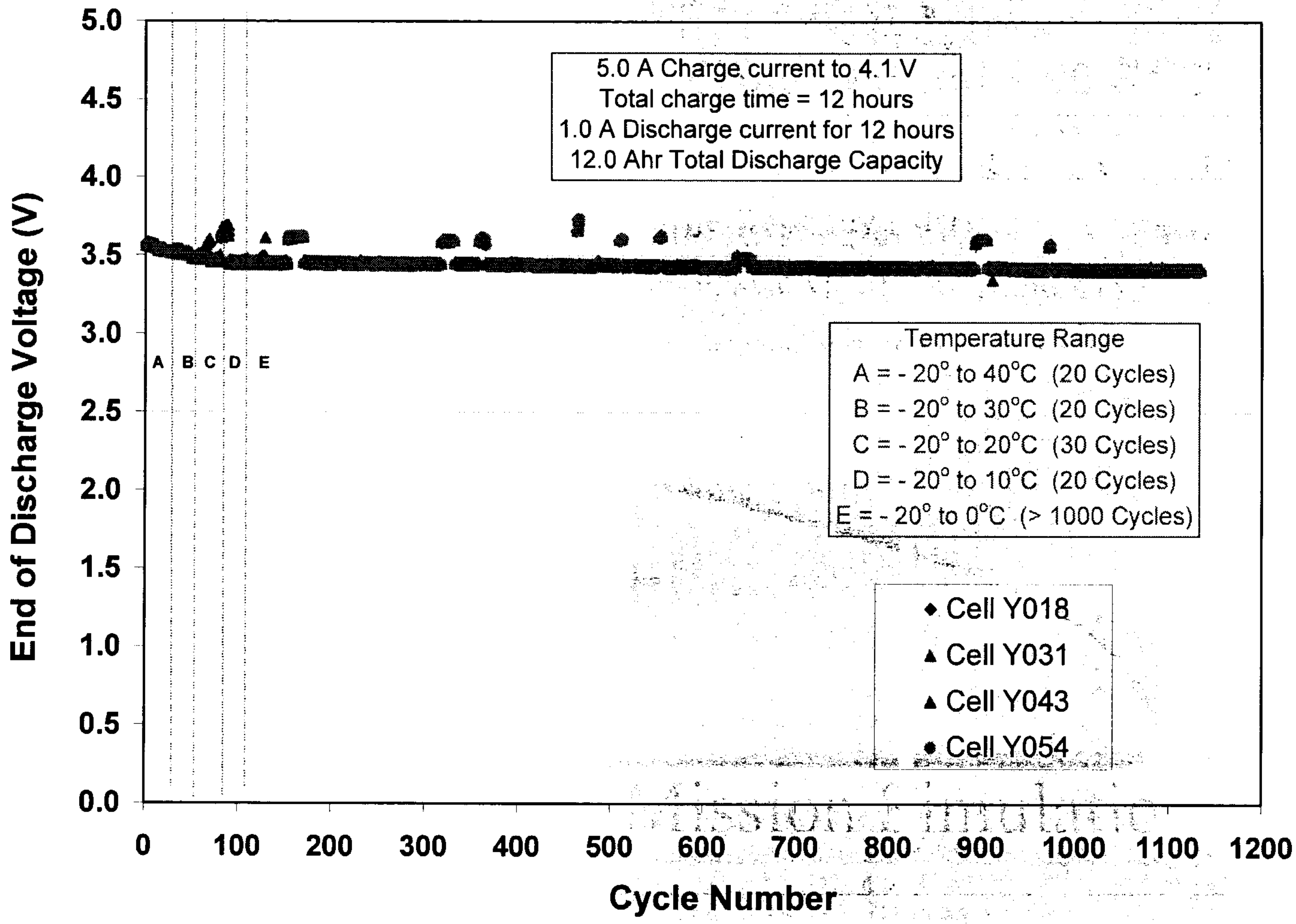
Characterization After Cruise Period + 90 Sols

Capacity at 20°C (After Cell Balancing)



- Capacity prior to cruise period = 9. 898 Ah at 25°C, and C/5
- 98.4% Capacity retention after cruise + 90 Sols of operation

Mars Lander (MSP01) Mission Simulation Test



- Similar chemistry as MER cells.
- Test included 10 months cruise at 10°C. Cycling at 50% DoD
- Demonstrated over 1000 sols and an overall calendar life of about 5 years.

Summary

- The Lithium Sulfur Dioxide primary batteries were successfully depassivated via constant voltage discharge and powered all the EDL operations of Spirit and Opportunity.
- The Lithium ion rechargeable batteries on both the Spirit and Opportunity are performing nominally, despite some deep discharge experienced on Spirit.
- The ground data project little capacity loss of less than 3% during cruise and 90 sols.
- Batteries are poised to extend the mission beyond six months, if not a couple of years.

Acknowledgment

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